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IN THE UNITED STATES DISTRICT COURT
FOR THE NORTHERN DISTRICT OF CALIFORNIA
SAN FRANCISCO DIVISION

FULLVIEW, INC., a Delaware corporation, Plaintiff, vs. POLYCOM, INC., a California corporation, Defendant.	§ § § § § § § § § § §	Case No. 3:18-cv-00510 **JOINT CASE MANAGEMENT STATEMENT** Hearing: Case Management Conference Judge: Hon. Edward M. Chen Venue: Courtroom 05, 17th Floor Date: October 12, 2021 Time: 2:30 pm

Plaintiff FullView, Inc. ("FullView") and Defendant Polycom, Inc. ("Polycom") (collectively, "the Parties") submit this Case Management Statement pursuant to the *Civil Standing Order – General U.S. District Judge Edward M. Chen*.

1. <u>Case Status and Upcoming Dates</u>

As the Court may recall, the parties have been trying to settle this case or, in the alternative, have been exploring procedural options that would allow FullView an opportunity to appeal the Court's previous decision that one of the two asserted patents was invalid for failure to comply with 35 U.S.C. § 101. When the parties reported that they had reached an impasse at the August 10, 2021 Case Management Conference, the Court set a March 10, 2022 date to hear the parties' motions for summary judgment of invalidity and ordered the parties to work out a refined stipulated schedule, including fact discovery deadlines, expert reports and briefing. (ECF 154.) Soon after the CMC, the parties served discovery on each other.

Polycom's Position:

In light of important newly-discovered information described below, Polycom intends to file a motion for leave to amend its Answer to include counterclaims of inequitable conduct and invalidity due to the on-sale bar and to amend its invalidity contentions to include the Nalwa 1996 paper and the apparatus discussed in Majumder paper described below. Polycom only recently learned of the apparatus described in the Majumder paper and that the Nalwa paper was both known and publicly-available when discovery in this case became active following the last CMC. Polycom requests that the Court continue the March 10, 2022 hearing date so that Polycom may move for leave to amend its Answer. Because the Court's decision on Polycom's forthcoming motions will materially impact the scope of Polycom's invalidity case against FullView, additional time is needed to complete fact discovery and expert discovery after such ruling.

In connection with the Court's August 10, 2021 order, Polycom began interviewing potential expert witnesses. One potential expert—a research engineer in the Department of Computer Science at the University of North Carolina—indicated that he had built a panoramic

viewing apparatus meeting all the limitations of the asserted claims of the ’143 patent before the August 28, 1998 filing date of the application leading to the ’143 patent. Polycom’s counsel is currently investigating the facts and circumstances surrounding the public availability of this apparatus. To show us a picture of the device, the expert provided Polycom’s counsel with a 1999 paper written by Majumder (and others) including a figure depicting the expert’s apparatus, which was a joint venture among the University of North Carolina, Brown University, and the University of Utah, as shown below:

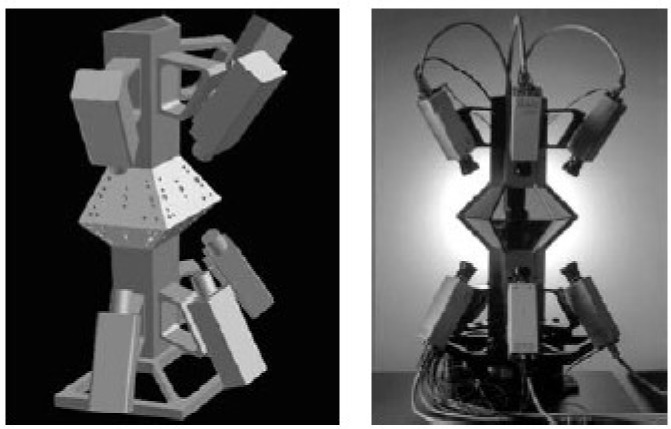

Figure 2: One side of the Camera Cluster

Importantly, the Majumder paper also described previously known panoramic viewing apparatuses, including one developed by Dr. Nalwa (the inventor of the ’143 patent) and described in a January 1996 paper cited by Majumder. The Nalwa 1996 paper includes several figures that are substantially similar to the figures in the ’143 patent, as well as a photograph of a prototype device that appears to meet all limitations of the asserted claims of the ’143 patent. The footer of the Nalwa 1996 paper is stamped with a legend that reads, “Bell Laboratories Technical Memorandum, BL0115500-960115-01, © 1996 Bell Labs.” Counsel for Polycom was aware of this 1996 paper, which appeared to be an internal Bell Labs document; but previously was unaware that the Nalwa 1996 paper had been known to others and was publicly

available before the priority date of the ’143 patent. The 1996 Nalwa paper describing and depicting the alleged invention of the ‘143 patent was not disclosed in any filings that FullView made to the USPTO in prosecuting any of the over one dozen patents in its portfolio. Thus, upon seeing this reference to the Nalwa 1996 paper, counsel for Polycom began investigating whether the Nalwa 1996 paper had been publicly disclosed prior to August 28, 1998. Through that investigation, Polycom discovered multiple references citing and describing the contents of the Nalwa 1996 paper earlier than the filing date of the application leading to the ’143 patent, demonstrating that the Nalwa 1996 paper was prior art to the ’143 patent known by the inventor that should have been disclosed to the Patent and Trademark Office during prosecution.

As soon as these facts became known to and were confirmed by Polycom’s counsel, Polycom provided the information to FullView’s counsel and in a letter dated September 27, 2021 and advised of its intent to move the Court to allow Polycom to amend its invalidity contentions and amend its answer to add a counterclaim alleging inequitable conduct. FullView responded on September 28 advising that it would oppose any Polycom motions and stated, among other things, that “[t]here is no disclosure or suggestion in [the] Nalwa 1996 [paper] that is claimed in the ’143 Patent.” This statement, however, flatly contradicts FullView’s Interrogatory Response No. 1, served on September 22, 2021 in which Dr. Nalwa stated, under oath, that “[t]housands of individuals worldwide became aware of the invention” between 1995–1998 and “saw a prototype of the invention or read the technical memorandum that described it,” i.e., the Nalwa 1996 paper. Further, FullView produced the Nalwa 1996 paper for the first time on September 22, 2021 with its interrogatory responses and responses to requests for production. Further, FullView’s Response admitted that several individuals from around the world traveled “to meet with the inventor and seek business arrangements with him and his employer” during this same 1995–1998 timeframe.

In light of these developments, Polycom plans to move for leave to amend its Answer and Counterclaims and invalidity contentions as set forth above, and proposes continuing the March 10, 2022 hearing and setting a date for a joint hearing on the parties’ summary judgment

motions and, if Polycom is allowed to amend its answer, an evidentiary hearing on inequitable conduct to take place six months after a ruling is issued on Polycom's motion to amend both its contentions and answer.

With regard to FullView's position below, Polycom takes issue with the accusations of duplicity and misrepresentation that FullView flings at it. They are false, offensive, and wholly unsupported by the record. As this Court has observed, Polycom has proceeded in good faith at all times and will continue to do so.

Further, it seems that FullView has taken this Case Management Statement as an opportunity to argue the merits of Polycom's intended motion for leave to amend its invalidity contentions and answer. However, at this juncture, Polycom is simply asking that the Court build time into the schedule for briefing and resolution of Polycom's motion for leave to amend and provides a short background for the same. The merits of Polycom's position and the good cause for its requests will be set forth fully in its forthcoming motion and supporting brief, and as such, Polycom does not provide a response to FullView's substantive positions herein. With regard to the schedule, Polycom submits that it is not seeking to delay the case in bad faith but rather to ensure a complete record based on discovery and information learned once the prosecution of the case began in earnest after the August 2021 CMC when formal discovery was served in light of the parties' impasse as to settlement.

FullView's Position:

It is FullView's position that Polycom's raising of new art at this point in the proceeding is unexplained and its reasoning duplicitous. This is not the first instance in which Polycom has misrepresented the facts or sought to undermine the Court's proceedings.

During claims construction, Polycom misrepresented that the examiner in the PTO's initial consideration of the application that led to the '143 Patent characterized "a 'pyramid shaped element' as 'a combination of a plurality of reflective elements'" when the examiner did no such thing. ECF 117 at 4:23-24. In the same proceeding, Polycom misrepresented Figure 13 of the patent as depicting shades to be part of the "pyramid shaped element," ECF

117 at 8:2-3, when the patent specification specifically stated: "FIG. **13** illustrates the pyramid of FIG. 12 with shades positioned in blind regions" (3:25–26).

In the same proceeding, after hours of tutorials and hearings and numerous suggestions of potential constructions by the Parties and the Court, in a final salvo, Polycom suggested to the Court in an email on April 17, 2021 that the Court adopt a circular construction: "A 'pyramid shaped element' is a pyramid-shaped element, except that its apex and base may be absent or incomplete." In other words, in a last-ditch effort, Polycom sought to negate the claims construction proceedings almost entirely. Polycom's present enterprise is similar.

Having lost its position on the construction of "pyramid shaped element" entirely, Polycom now raises the following two issues for which it must again rely on disingenuous assertions that are intended to confuse and mislead the Court. In addition, Polycom intentionally tries to conflate these two issues even though they are independent of each other.

1. Polycom seeks leave to amend its answer to add a counterclaim based on the "Nalwa 1996" reference not being disclosed to the patent office.
2. Polycom seeks leave to amend its Invalidity Contentions to add a reference to a Majumder device.

Each such request would be without good cause, untimely, prejudicial to FullView and futile.

FullView asserted infringement by Polycom of the '143 Patent on January 23, 2018, in FullView's original complaint. On January 31, 2019, almost a year later, Polycom pursued its unsuccessful petition to PTAB for *Inter Partes* Review ("IPR") of the '143 Patent. This petition was accompanied by an 88-page expert declaration. Polycom had a second opportunity to retain experts and conduct a full search for prior art that might have a bearing on the invalidity of the '143 Patent before serving its Invalidity Contentions on FullView more than a year ago and more than a year after the IPR Decision. In both instances, Polycom also had a full opportunity to investigate Nalwa 1996. In analogous circumstances, when FullView requested leave to amend its complaint, Polycom counted the days that had elapsed since various events, ECF 129 generally, but here the delay is beyond days or months and into years.

Majumder

First, Polycom is unable to explain why due diligence by it could not have led it to discover the Majumder reference in a timely fashion. Indeed, Polycom does not show that it or its various counsel working on these matters did not in fact discover the Majumder reference previously. Rather, Polycom simply asserts that a potential expert "provided Polycom's counsel with a 1999 paper written by Majumder." No explanation is given why Polycom did not interview this potential expert before serving its Invalidity Contentions on FullView over a year ago. That Majumder's paper cites Nalwa 1996 is irrelevant and does nothing to explain why this circumstance is not more prejudicial and more untimely than Polycom vociferously alleged was FullView's proposed amendment to its complaint:

> Claim construction briefing is finished, and the claim construction tutorial took place on March 9, 2021. Dkts. 116-118. The claim construction hearing is scheduled to proceed on March 23, 2021. Dkt. 79. The parties have also exchanged infringement and invalidity contentions as well as damages contentions and responses related to the '143 Patent.
>
> … Irrespective of the above arguments, FullView's third attempt to amend the complaint should be denied based on undue delay and prejudice to Polycom.

ECF 129 at 2-3 and 12. An amendment by Polycom of its Invalidity Contentions now would indeed be highly prejudicial to FullView not only for the reasons Polycom cites above, but also because FullView relied on Polycom's Invalidity Contentions for claim construction.

FullView cannot address the merits of Majumder here when all Polycom has presented is an insinuation. At a minimum, FullView must first receive a fully supported motion for leave to amend before FullView addresses the merits of Polycom's claims about the teaching, including claimed further evidence that it says it is still collecting, in relation to Majumder.

Nalwa 1996

Second, Polycom is unable to explain why due diligence by it could not have led it to discover in a timely fashion that the Nalwa 1996 reference was in the public domain prior to the filing of the '143 Patent application. Indeed, Polycom does not show that it in fact has not known for years that Nalwa 1996 has been in the public domain since 1996.

Polycom served its first set of interrogatories and its first set of requests for documents on FullView on August 23, 2021, to which FullView responded on September 22, 2021. FullView served its first set of requests for documents on Polycom on September 8, 2012. A response to this FullView request is due by October 8, 2021.

In its response to Polycom's first set of request for documents, FullView *inter alia* produced this technical memorandum ("TM") published at Bell Labs on January 15, 1996: "A True Omni-Directional Viewer," Vishvjit S. Nalwa ("Nalwa 1996"). Exhibit A. This TM's sole author is Dr. Nalwa, who is also the sole named inventor of the '711 and '143 Patents. This TM's publication date, January 15, 1996, is after the priority date of the '711 Patent, namely, November 30, 1995, and before the priority date of the '143 Patent, namely, August 28, 1998.

In response to this disclosure, Polycom alleged in a letter to FullView that FullView's failure to disclose Nalwa 1996 to the patent office upon filing FullView's '143 Patent application constituted inequitable conduct because Figure 18 of the TM "discloses the panoramic viewing apparatus described in at least claims 10–12 of the '143 patent".

FullView responded to Polycom's letter with its own letter, which read in part, "There is no disclosure or suggestion in Nalwa 1996 that is claimed in the '143 Patent," and:

> A dated copy of this document has been available on FullView's website for well over a decade: http://www.fullview.com/A_True_Omni-Directional_Viewer.pdf. Your letter makes no effort to explain why or whether any due diligence conducted by Polycom in preparing its Invalidity Contentions could not have led it to discover Nalwa 1996, which is and has been widely available and cited despite being initially published as a Bell Labs Technical Memorandum, rather than in a conference proceeding or in a journal. *See,* for instance, https://scholar.google.com/, https://www.semanticscholar.org and https://patft.uspto.gov/, and do a search for the publication or its author. The first two of these three well-known websites even link to the copy of Nalwa 1996 on FullView's website.

When FullView responded thus, Polycom had not alleged it knew of Nalwa 1996, but only not that Nalwa 1996 had been in the public domain since before the '143 Patent application.

Instead of explaining above why it is only now raising Nalwa 1996 and whether and what due diligence it conducted, Polycom embarks on a series of questionable assertions in this CMC statement — assertions that beggar belief or are demonstrably false.

One, Polycom states in "Polycom's Position" above:

> Counsel for Polycom was aware of this 1996 paper, which appeared to be an internal Bell Labs document; but previously was unaware that the Nalwa 1996 paper had been known to others and was publicly available before the priority date of the '143 patent.

But Polycom did not acknowledge in its letter that it knew of Nalwa 1996 prior to FullView's providing Polycom a copy of this TM. If Polycom was aware of Nalwa 1996 as it claims, a publication that is time stamped in its header, why did Polycom not simply do a search on Google, or more specifically on Google Scholar, to see if this TM was referenced by anyone before the '143 Patent application.

But even this new tack by Polycom — that it knew of Nalwa 1996, but did not know that Nalwa 1996 was in the public domain before the '143 Patent application was filed — is apparently false. A key reference in Polycom's Invalidity Contentions is this paper, of which Polycom provided FullView only an illegible copy, Exhibit B: "Generation of High-resolution Stereo Panoramic Images by Omnidirectional Imaging Sensor Using Hexagonal Pyramidal Mirrors," Kawanishi, T., Yamazawa, K., Iwasa, H., Takemura, H., and Yokoya, N., *ICPR*, vol. 1, pp. 485-489, August 16-20, 1998 ("Yamazawa 1998"). It turns out that Yamazawa 1998, which predates the '143 Patent application, also cites Nalwa 1996, as Reference 7, as the paper's publisher IEEE reveals, Exhibit C, even though one cannot surmise this from the paper's illegible copy that Polycom provided. Putting aside any other consideration, Polycom had and has a duty to furnish legible documents to FullView and the Court. FullView repeatedly asked it for a legible copy of Yamazawa 1998 to no avail. Even assuming that Polycom in fact did not have a legible copy of Yamazawa 1998 when it served its Invalidity Contentions on FullView, if Polycom had done its duty to provide a clear copy of this paper to FullView at its earliest, Polycom would have long discovered that Nalwa 1996 was in the public domain before the '143 Patent application was filed.

A more plausible explanation than Polycom's for why it did not cite Nalwa 1996 or any prior art that cited Nalwa 1996, other than to provide a garbled copy of one — that it did not

know Nalwa 1996 was in the public domain since its publication — is this: Before the Court dismissed all allegations related to the ’711 Patent, which was before Polycom had to serve its Invalidity Contentions on FullView, Polycom was loathe to reveal to the Court that the non-patent counterpart of the ’711 Patent, Nalwa 1996, was widely recognized in the art as groundbreaking, as evinced by its widespread citation. But with the ’711 Patent out of the way, at least for now, Polycom has no such constraint.

Two, Polycom argues, “The Nalwa 1996 paper includes several figures that are substantially similar to the figures in the ’143 patent …” As Polycom’s attorneys should know by now, after more than a decade of litigation, the ’143 Patent includes substantially all the disclosures of the ’711 Patent and that all the figures that Polycom is referring to first appeared in the ’711 Patent, which preceded Nalwa 1996. Nalwa 1996 has none of the figures of the ’143 Patent that show “a support member intersecting an inner volume of the pyramid shaped element” (claim 10), which was new in the ’143 Patent over the ’711 Patent. That is, Nalwa 1996, does not show any drawing similar to Figures 17, 18 and 19 of the ’143 Patent.

Three, Polycom states, “The Nalwa 1996 paper includes … a photograph of a prototype device that appears to meet all limitations of the asserted claims of the ’143 patent.” Polycom knows, or should know after the IPR Proceedings — in which Polycom submitted the prosecution history of the ’143 Patent as an exhibit — and from the arguments presented in those proceedings and in the claims construction proceedings in this case, that this assertion is false. What the photograph in Figure 18 of Nalwa 1996 depicts in regard to the intersection claimed by the asserted claims is no different from what is shown in Figure 10 of the Herndon patent, which was overcome in the prosecution history and was the basis of the IPR Decision. Moreover, Figure 18 is identical in this regard to the Bowie prototype whose photograph Dr. Nalwa reproduced in his declaration to both PTAB and this Court, in both instances to describe the state of the art prior to the ’143 Patent.

Finally, Polycom alleges:

> Dr. Nalwa stated, under oath, that "[t]housands of individuals worldwide became aware of the invention" between 1995–1998 and "saw a prototype of the invention or read the technical memorandum that described it," i.e., the Nalwa 1996 paper. Further, FullView produced the Nalwa 1996 paper for the first time on September 22, 2021, with its interrogatory responses and responses to requests for production.

FullView's response to Polycom's first set of interrogatories is imperative here. Exhibit D. What Dr. Nalwa said under oath in response to Polycom's Interrogatory No. 1 was this, "There was thorough diligence by the inventor over 1995-1998 and beyond …" Polycom just dropped "and beyond." And the "invention" being referred to can be surmised in context to be that of the '711 Patent with and without the invention of the '143 Patent. Polycom could not have misunderstood this because Dr. Nalwa also said in the same response that, "The asserted claims were reduced to practice in 1999-2000: A product that implemented these claims was sold to USC around May 2000." And if there still remained any doubt, Dr. Nalwa said under oath in response to Polycom's Interrogatory No. 4: "Before the filing of the patent application on August 28, 1998, the inventor and his employer at the time, Bell Laboratories, kept the invention [of the asserted claims] in strict confidence."

FullView urges the Court to see Polycom's leave to amend its answer for what it is: a decoy to distract the Court into granting Polycom leave to amend its Invalidity Contentions without good cause, granting which would not only be highly prejudicial to FullView, but also delay the schedule needlessly.

Dated: October 5, 2021

HAUSFELD LLP

/s/ *Bruce J. Wecker*

Bruce J. Wecker

Counsel for Plaintiff FullView, Inc.

Dated: October 5, 2021

WINSTON & STRAWN LLP

/s/ *Katherine Vidal*

Katherine Vidal

Counsel for Defendant Polycom, Inc.

ECF CERTIFICATION

I, Bruce Wecker, am the ECF user whose ID and password are being used to file this **JOINT CASE MANAGEMENT STATEMENT**

I hereby attest pursuant to General Order 45.X.B. that concurrence in the electronic filing of this document has been obtained from the other signatories.

DATED: October 5, 2021

/s/ *Bruce J. Wecker*
Bruce J. Wecker

CERTIFICATE OF SERVICE

I, Bruce Wecker, declare that I am over the age of eighteen (18) and not a party to the entitled action. I am of counsel at the law firm of HAUSFELD LLP, and my office is located at 600 Montgomery Street, Suite 3200, San Francisco, California 94111.

On October 5, 2021 I caused to be filed the following:

JOINT CASE MANAGEMENT STATEMENT

with the Clerk of the Court using the Official Court Electronic Document Filing System which served copies on all interested Parties registered for electronic filing.

I declare under penalty of perjury that the foregoing is true and correct.

DATED: October 5, 2021 /s/ *Bruce J. Wecker*

Bruce J. Wecker

EXHIBIT A

"A True Omni-Directional Viewer,"

Vishvjit S. Nalwa,

Bell Labs Technical Memorandum,

BL0115500-960115-01,

January 15, 1996

("Nalwa 1996")

A True Omni-Directional Viewer†

Vishvjit S. Nalwa
AT&T Bell Laboratories
Holmdel, NJ 07733, U.S.A.

Abstract

I describe here the design of what I believe is the first true omni-directional camera: a camera that can capture, at any instant, a 360° view of a scene effectively from a single viewpoint. My design is simple and robust, and extends easily to accommodate the following: projectors, rather than imagers, viewers that image/project most of the visual sphere, rather than just a visual cylinder, and viewers that provide high-resolution views using low-resolution viewing devices. An instance of my design that has been implemented and I shall outline provides a live seamless 360° view of a scene using four individual CCD cameras, each camera with a 90°+ field of view and viewing the scene off a face of a mirrored pyramid.

† The commercial interests of AT&T Bell Laboratories in this work are protected by numerous patents filed in the U.S.A. and other countries.

Contents

1. Introduction

I propose here what I believe is the first design of a true omni-directional camera: a camera that can capture, at any instant, a 360° view of a scene effectively from a single viewpoint. I shall describe this design and explain why other previously proposed designs do not provide true omni-directional views. Then, I shall outline an implementation of my design and describe this implementation's performance.

My design is truly simple: It is based on the principles of two well-known optical devices, the pinhole camera and the planar mirror. The principles of these devices have been well understood for several centuries—probably since Kepler in the early seventeenth century—and their operation has been observed for at least another 2000 years, at least since the fifth century B.C., when Mo Ti recorded his observations in China on the operation of a pinhole camera (see [Rosenblum 1989] and [Ronchi 1957]).

In addition to its conceptual simplicity, my design is robust, requires minimal hardware and computation, and extends easily to accommodate the following: projectors, rather than imagers, viewers that image/project most of the visual sphere, rather than just a visual cylinder, and viewers that provide high-resolution views using low-resolution viewing devices.

An instance of my design that has been implemented provides a live seamless 360° view of a scene using four individual CCD cameras, each camera with a 90°+ field of view and viewing the scene off a face of a mirrored pyramid. Competing designs fall broadly into one of four categories, each with its own one or more shortcomings: They comprise multiple ordinary cameras looking out into the scene directly in different directions, and, hence, they work on only scenes with no object close to the omni-directional camera; their lenses rotate, and, hence, they work on still scenes only; and, they use either single nonplanar mirrors or single fish-eye type lenses, and, hence, do not view the scene effectively from a single viewpoint and typically offer lower-than-normal image resolution.

Potential applications of an omni-directional camera include use in interactive television, in surveillance systems, in video conferencing, and in home shopping. **A key benefit of an omni-directional camera is that several users can simultaneously, independently, and perhaps remotely view the complete 360° panoramic image and individually choose from it a narrower view in any direction in greater detail.** This view, in effect, is provided by a virtual ordinary camera whose pan—and to a limited extent, tilt and zoom—is under each user's complete simultaneous control. Recall that **pan** refers to camera rotation about the vertical axis, **tilt** to its rotation about a horizontal axis, and **zoom** to image magnification by narrowing the camera's field of view.

2. Fundamentals

As I mentioned in the introduction, the design I have in mind is very simple. However, before I can explain it to you, we must recall a few key fundamentals of imaging—described at length, for instance, in [Nalwa 1993]:

1. *A typical camera with a lens is an attempt simply to replicate the geometry of a pinhole camera.* Figure 1 illustrates a pinhole camera. The reason for using a lens in a typical camera is to keep the image sharp and unblurred while we increase the image brightness by employing an aperture much larger than a pinhole.

2. *The geometry of image formation in a pinhole camera follows perspective projection of the scene onto a plane up to an inversion, with the center of projection at the pinhole.* Figure 2 illustrates perspective projection. Then, for all purposes of reasoning and analysis, we may consider the plane on which the image is formed in a pinhole camera to be in front of the pinhole, rather than behind the pinhole.
3. *The surface in a pinhole camera on which an image is formed, or equivalently, the surface on which we consider the scene to be perspectively projected, need not be planar at all.* It could be any non-self-occluding surface of known shape, as illustrated in Figure 3, and, we would, in principle, have exactly the same information as we would in a planar image.

In other words, **all the information in a pinhole image can be represented as a continuum—or, in the case of a discrete image, as a collection—of light rays toward a single viewpoint, each ray with a particular orientation, brightness, and color.** This completes our recollection of some fundamentals of imaging.

3. The Task

The task we face is designing a true omni-directional camera. **I define a true omni-directional camera as one that can provide an image of the surrounding world, all 360° around, at any given instant from a single viewpoint.** As shall soon become apparent, the challenge in this task is conceptually equivalent to that in designing a projector that can project an image all 360° around at any given instant from a single viewpoint.

A typical camera can image the world around only within a circular cone that is no more than about 60° at its vertex, as shown in Figure 4(a). What we are seeking is to extend this typical camera's field of view to encompass all 360° around in one dimension, as illustrated in Figure 4(b).

In my definition of a true omni-directional camera, I have included two criteria over and above that the view should encompass 360° in one dimension. One, the complete 360° view should be available at any given instant; this criteria is necessary to ensure that moving objects in the world appear coherent and unblurred in the image. Two, the 360° view should be from a single viewpoint, or, in the terminology of the preceding section, the complete 360° view should have a common center of projection. This criteria allows us to reconstruct from each omni-directional view, typical narrower-angle views that are perspective projections of the scene, which we are accustomed to seeing—with straight lines in the scene appearing as straight lines in planar images for instance. As far as I can tell, no existing

design of an omni-directional camera satisfies both these criteria simultaneously.

4. The Problem

Now, assuming the pinhole geometry for each camera, **the problem we face in designing an omni-directional camera from multiple pinhole cameras is that we must colocate the multiple pinholes, each pinhole directed to capture a different set of light rays, without one camera obstructing the view of another.** This problem is illustrated in Figure 5. As is well known—see, for instance, [Nalwa 1993]—the farther away the pinholes are from each other, the greater shall be the disparity between their images within the common fields of view of the pinholes. This disparity, of course, is the basis of stereo vision. And the greater this disparity, the more difficult it shall be to combine the individual images into a single coherent omni-directional image. I am assuming here that we do indeed want to use multiple cameras to accomplish our task at hand. I shall address the problems we face when trying to use a single camera for omni-directional viewing when I outline alternatives to my design.

A simple calculation illustrating the disparity in the views of multiple pinhole cameras whose pinholes are not colocated is instructive here. Consider Figure 6, which shows two pinholes P_1 and P_2, located a distance D apart. Now, consider two rays r_1 and r_2 from a point at infinity toward the two pinholes P_1 and P_2, respectively, the point at infinity located along the perpendicular bisector of the line connecting the two pinholes. These two rays, with identical orientations, but displaced a distance D apart, provide a reference direction for the two views from the two pinholes. Now, consider a point P in the scene, this point along the perpendicular bisector of the line connecting the two pinholes and at a distance d from that line, as shown. We have located our scene point P as described only to make our argument simple, but not at the expense of generality. Now, it is clear that the clockwise angle θ between the ray from the point P toward the pinhole P_1 with respect to the ray r_1, is the same as the anticlockwise angle ϕ between the ray from the point P toward the pinhole P_2 with respect to the ray r_2. In other words, the angular disparity between the images of point P in the pinhole cameras P_1 and P_2 is simply 2θ, which a simple calculation reveals to be $2\tan^{-1}(D/2d)$. As highlighted in Section 2, it is the orientation, color, and brightness of each ray that contain all the image information pertaining to the source of the ray, and we have just shown that **the disparity in the orientations of the two (rays**

forming the) images of a single point in two pinhole cameras increases as we increase the displacement between the two pinholes and decreases as we increase the distance of the point from the two pinholes. This observation is quite general, even though the geometry from which we arrived at it here is not so general.

5. The Solution

The solution to colocating multiple pinholes, without one pinhole camera obstructing another's view, is to use one or more planar mirrors. Figure 7 illustrates the image *I* of a point *S* in a planar mirror, as explained by Kepler. Whereas this geometry of reflection in a planar mirror is so familiar to us today, if we consider that it was first elucidated by Kepler in 1604 "after so many centuries of bafflement and confusion, Kepler's explanation seems simply marvelous" [Ronchi 1957].

Now, returning to the geometry of reflection in a planar mirror shown in Figure 7, if a pinhole of a pinhole camera is located at point *S*, it shall be mapped to point *I* by the planar mirror *M*. Then, the image of the world—in this case, of the two eyes shown—seen from *S* off *M* shall be the same as the image that would be seen directly from *I*, except for the familiar left–right reversion. Thus, **a planar mirror effectively maps a pinhole's view to that from the pinhole's mirror image, except for a left–right reversion**.

6. The Design

Now, if we had two planar mirrors, we could, in effect, colocate two pinholes using the mirror arrangement shown in Figure 8. This brings us to my design: **My design of an omni-directional camera consists of a mirrored *n*-sided pyramid with a pinhole camera looking off each side of the pyramid such that the mirror image of every pinhole (in the mirror the pinhole looks off) lies at the same location in space.** Figure 9 illustrates this design with a 4-sided pyramid. By an ***n*-sided pyramid** I mean a polyhedron, with $n+1$ faces in all, whose base is an n-gon and whose n sides extending from its base to its vertex are triangles. As we are concerned only with the surface of the pyramid off which our cameras see the world, our pyramid here could be partial—perhaps, with its base and vertex missing.

I have intentionally left the above statement of the design general to emphasize the variations possible within its framework. However, let us

now pin down several aspects of the design to simplify both its realizability and our discussion of it. First, let us assume that our mirrored pyramid is a **right regular pyramid**—that is, a pyramid whose base is a regular *n*-gon (a polygon with *n* identical sides and *n* identical corners) and whose vertex is perpendicularly above the center of its regular base. Then, each side of the pyramid extending from the base of the pyramid to its vertex shall be an identical isosceles triangle. Let us further assume that each triangular side of the pyramid forms a 45° angle with a plane parallel to the pyramid's base. Now, let us stand such a pyramid on its vertex with its base horizontal, as shown in Figure 9. Further, as also shown in the figure, let us position all the pinholes in the horizontal plane that contains the pyramid's vertex such that each pinhole is equidistant from the vertex and along the bisector of the horizontal projection of the vertex angle of the associated pyramid side. Then, as each pyramid side is at 45° to the horizontal plane, it is easy to see that the mirror images of all the pinholes shall coincide at that point in space on the axis of the pyramid that is the same distance from the vertex as the pinholes are from the vertex. If our cameras are now pointed vertically upward, they shall effectively view the world horizontally outward from a single point in space up to a lateral reversion, which is easy to undo.

Now, let us also assume that the imaging surface of each pinhole camera is a plane that is horizontal. Then, each triangular face of the mirrored pyramid shall be imaged as a rectangle of infinite extent, with the vertex of the pyramid being imaged at infinity in each pinhole camera, and the rectangular image oriented such that it is symmetric about the vertical plane containing the vertex and the pinhole. Can you see this? It has been a cause of considerable confusion to several individuals who have examined my design. An easy way to see this is to consider an object that is a rectangle of the type described, and let the plane of the associated pyramid side be the image plane, with the pinhole's position unchanged. Then, the vanishing point of the two infinite sides of the rectangle is easily seen to be at the vertex of the pyramid—see, for instance, [Nalwa 1993]—and because projection from one planar surface to another is completely reversible, we have our sought result.

Finally, yes, we have limited ourselves only to pinhole cameras to this point, not because we plan to use such cameras, but because a pinhole camera provides a very useful approximation to the geometry of most cameras with lenses. Under this approximation, the pinhole corresponds to the **optical center** of the lens if the camera lens is thin. More generally, as illustrated in Figure 10, the pinhole corresponds to the **first nodal point** or

forward nodal point of the camera lens as far as rays from the world to the lens are concerned, and to the **second nodal point** or **rear nodal point** of the camera lens as far as rays from the lens to the imaging surface are concerned. Figure 10 also illustrates the **optical axis** of the lens, which is the axis of rotation of the lens; the two nodal points lie on this axis. Thus, from a geometrical point of view, a typical lens can be approximated by two pinholes, an entrance pinhole, which corresponds to the forward nodal point, and an exit pinhole, which corresponds to the rear nodal point. When we refer simply to a pinhole of a camera with a lens, without further qualification, we shall be referring to its entrance pinhole. Of course, there are rays emanating from any object point that enter the lens through a path other than that toward the forward nodal point, such rays finally reuniting with the ray directed toward the forward nodal point at the image of the object point. It is the collection of such rays that makes the use of lenses desirable to begin with. The complete cone of light rays emanating from an object point that is gathered by a lens to from an image of the point is determined by the **entrance pupil** of the lens, which, in effect, is the imaging aperture of the lens. This entrance pupil, illustrated in Figure 10 in front of the forward nodal point of the lens, could as well be located at or behind the forward nodal point. For more on lenses, see the books by Cox [Cox 1974] and Hecht [Hecht 1987], especially the book by Cox, *Photographic Optics*, which provides the most lucid description of nodal points and other lens characteristics I have seen.

7. Alternate Designs

I promised you in the introduction that I would establish that other designs proposed for omni-directional cameras do not provide true omni-directional views, where a true omni-directional view is a 360° view available at any given instant from a single viewpoint—mathematically, from a single center of projection. As we shall see now, at worst, other designs do not provide an instantaneous 360° view, and, at best, they provide an instantaneous 360° view from a continuum of viewpoints, and with limited image resolution.

The obvious way to design an omni-directional camera is to pack together a collection of small cameras pointing in different directions, perhaps with their pinholes centered on the faces of a regular Platonic solid; see [Coxeter 1969] for an account of the five Platonic solids. There is a commercial product available based on this design (see [Anderson 1995]). When I first set out to design an omni-directional camera, I began by

considering such a strategy, using optical fibers to pack together lenses pointing in different directions, each lens at one end of an optical fiber at whose other end is an imaging surface. But a simple analysis, of the type in Section 4, quickly revealed that even if each lens was just half an inch in diameter, the disparity between adjoining images of an object several feet away from the lens packing would be too large to allow us to assemble directly the individual images into a seamless composite image. Under such circumstances, we could attempt to blend the images together at the seams, perhaps using sophisticated techniques, such as in [Burt and Adelson 1983], but blending is time consuming and guaranteed to degrade the image fidelity. Hence, I summarily rejected such an approach.

Then, three possibilities remain for the design of an omni-directional camera. We could either rotate our camera or lens about its pinhole, looking at different directions at different instants, or we could alter the optical paths of light rays from the world toward the pinhole—either by reflection or by refraction—such that we are able to image the world all around. My design, of course, alters the paths of light rays through reflection, but it is not the only such design. Let us now discuss, in turn, each of these three strategies to create omni-directional images.

7.1 Motion Based

Panoramic views have held a fascination for both photographers and the public at large since the very invention of photography, and rotating a camera or lens to create a panoramic view is the oldest approach toward this goal.

Photography was invented in the summer of 1827 by Joseph Nicéphore Niépce, who exposed a pewter plate coated with bitumen for eight hours in a *camera obscura* to obtain an image of a view from a window in his estate at Le Gras in France. Within 25 years of this invention, photographers were arranging, in contiguous order, series of individual photographs obtained by rotating a camera to depict a wider view than that possible with a single photograph. Before long, a 360° panorama had been created in this fashion—the first, probably a view of Chicago in 1859 by Alexander Hesler. See [Rosenblum 1989] for a comprehensive history of photography, and [Meehan 1990] for more on panoramic photography.

Similar efforts—to create 360° views from discrete images obtained by rotating a camera—have been reported more recently too, the emphasis of these efforts being on the creation of composite images that are visually seamless. See, for instance, [Focal 1969] under the topic *Panorama*, [Dixon

1989], [Szeliski 1994], [McMillan and Bishop 1995], and [Chen 1995], the last of these efforts leading to a commercial product (see [Halfhill 1995]).

It is not hard to see that if we want an omni-directional view from a single viewpoint using such an approach, we must rotate the camera about its forward nodal point. Else, the resulting view shall not be from a single viewpoint, and also we shall have to expend considerable effort to produce a seamless result from the individual images.

An alternative to acquiring discrete views by rotating a camera, and then merging these views into a single 360° view, is to build up a 360° cylindrical view by sweeping over the imaging surface an image through a slit while rotating the camera about an axis parallel to this slit. This approach, which too has its origins in the mid-nineteenth century, has traditionally been the most popular method of creating a 360° image, with the venerable Kodak No. 10 Cirkut camera being its workhorse (see [Meehan 1990]). In this approach, the camera must rotate about its rear nodal point if we wish to keep the images of distant points sharp (see [Cox 1974]). But, then, the images of points close to the camera will not be as sharp, and, further, the complete image will not be acquired from a single viewpoint, but from a circular collection/continuum of viewpoints, the radius of this circle being the distance between the forward and rear nodal points. More recent efforts based on this approach, employing electronic rather than film cameras, include [Zheng and Tsuji 1990] and [Krishnan and Ahuja 1993].

The primary disadvantage of a motion-based approach to creating an omni-directional view is, of course, that the view is not instantaneous, and, hence, incapable of capturing moving objects that are arbitrarily located sharply and coherently. The total time required to acquire a 360° view in a scanning-slit camera can be anywhere from a second to a few minutes, several seconds being typical (see [Meehan 1990]). Two additional causes of concern in a scanning-slit camera are uniformity of mechanical motion, lack of which leads to uneven exposure, and synchronization of camera motion with image capture, lack of which leads to image distortion even for stationary objects. Further, the strategy of combining discrete individual images typically requires considerable post processing of images, and the strategy of sweeping a cylindrical image provides a view from a circular collection/continuum of viewpoints, as already explained.

7.2 Reflection Based

This approach has again apparently been around for over a century. A passing reference is made to it in [Meehan 1990] without any details, where it is mentioned that designers had tried conical mirrors to extend the field of view of a lens. A direct way to use a conical mirror to create a panoramic view is to place the mirror right above the lens, as shown in Figure 11, with the vertex of the conical mirror—the cone of this mirror assumed to have a right circular cross section—facing the lens, and its axis aligned with the optical axis of the lens. Such an approach has been outlined recently in [Jarvis and Byrne 1988] and [Yagi and Yachida 1991]. An alternative to using a conical mirror is to use a mirror of another shape, such as a sphere.

The fundamental problem with viewing the world off a nonplanar mirror is that the rays of light that eventually form the image do not all share the same viewpoint. To establish this, consider the pinhole of the lens in Figure 11—that is, its forward nodal point—and then consider the paths of individual rays from the world, off the mirror, and toward the pinhole. What you will observe from the figure is that the rays that come off the left and right edges of the conical mirror have different effective (virtual) pinholes: The effective pinhole for the rays on the right is at the reflection of the actual pinhole in the tangent plane to the right edge of the cone, and, similarly, the effective pinhole for the rays on the left is at the reflection of the actual pinhole in the tangent plane to the left edge of the cone. Then, it is clear that the world viewed off a conical mirror whose vertex is above the pinhole, as in all previously proposed designs, is viewed (virtually) from a continuum of viewpoints that lie on a circle, as illustrated in the figure. Similar arguments apply to every nonplanar mirror, except that, in general, the viewpoints shall lie not on a curve, but on a surface, as would be the case for a sphere for instance. Returning to the conical mirror, it is now clear that if we wish to reduce the circle of viewpoints to a single point, we must colocate the (physically absent) vertex of a truncated conical mirror with the pinhole itself, but then we might not have much of a useful view of the world.

In our discussion here to this point, we have assumed a pinhole aperture implicitly. Now, as we discussed in Section 2, in practice, to increase the image brightness we must use an aperture larger than a pinhole. But as we increase the aperture size here, not only shall we increase the image brightness, but we shall also increasingly blur the image due to our use of a nonplanar mirror. To see this, reconsider Figure 7, replacing an eye with a lens, and then noting the impact of the mirror M

being nonplanar on light rays emanating from the object point *S*, off *M*, toward the lens. Clearly, these rays will not appear to originate from a single (virtual) point in space, and thus, they will be imaged as originating from various points in space. As a result, the image of the object point will be blurred, the extent of this blurring depending on the total curvature of the intersection of the mirror with the cone of rays collected by the lens to form an image of the object point. This curvature depends not only on the shape and location of the mirror—the farther away the mirror from the lens, and the flatter its local shape, the less this curvature—but also on the aperture size, increasing which increases this curvature. Thus, when we use a nonplanar mirror, our maximum usable aperture size is limited by the mirror. To ease this limit, we may make our mirror have a low curvature and be distant from the lens, but then our effective viewpoints might have a locus with a greater spatial extent and our useful field of view might be further limited.

In addition to the lack of a single viewpoint with nonplanar mirrors, and limitations on the maximum usable aperture size, a practical problem with using a single camera is the resolution of the captured image: Capturing a 360° view on a single piece of standard film, or with an electronic imager—which nowadays is typically a charge-coupled device (CCD) array—provides inadequate image detail. Whereas, in principle, this limitation can be overcome if we are using film—by resorting to a larger than normal format—we are somewhat limited when imaging electronically. An electronic imager typically consists of an array of discrete sensors arranged in a rectangular grid, which is about 500 wide along each dimension. The size of this array can currently be increased to about a 1000 or so along each dimension, at a substantial price, but even that would not provide adequate resolution in the useful part of the captured image here. Note here also that, although large-format film might give us the resolution we are seeking, film cannot provide us live images, as can electronic imagers, and, in many applications, such as broadcast television, live images are what we seek.

Before we move on to the third approach, I would like to establish further connections between my work, which clearly belongs to the current category, and previous work. The use of a planar mirror to map the center of projection **from which** light rays are emanating is widespread and well-established in optics; see, for instance, the common overhead transparency projector. On the other hand, the use of a planar mirror to map the center of projection **toward which** light rays are directed seems to be less common—perhaps, because of an inadequate appreciation of the

connection between a camera with a typical lens and a pinhole camera. However, more than one example of such a use of a planar mirror is described in [Judd and Smoot 1989], where it is sought to increase the horizontal resolution of standard-resolution electronic cameras by combining images from multiple cameras.

7.3 Refraction Based

This is a fascinating approach, even though it is unable to provide omni-directional views from a single viewpoint. This approach is based on using so-called fish-eye lenses, which provide extremely large fields of view, even greater than 180°. This extremely large field of view is accomplished in a fish-eye lens by introducing one or more meniscus-shaped lens elements at the front of the lens to compress the desired field of view into a much smaller field that can be imaged by the rest of the lens. See Figure 12(a). In fact, there are fish-eye adaptors available, which when attached to the front of a normal lens, convert it to a fish-eye lens. It is clear that a fish-eye lens can provide us an omni-directional view at the fringe of its image. In fact, it does more: It provides a view of the top too. See [Kingslake 1989] for a brief introduction to fish-eye lenses.

Fish-eye lenses are not typical: They have large intentional image distortion, which is necessary to form an extremely wide-angle image on a limited-size flat surface. Further, fish-eye lenses do not obey the pinhole geometry at all—a geometry normal lenses try so hard to duplicate. For the arrangement shown in Figure 12(a), where the inner surface of the single meniscus is part of a sphere whose center at the center of the physical aperture of the lens below the meniscus, the locus of the effective viewpoints for light rays within the plane of the figure that are directed toward the center of the physical aperture after passing through the meniscus is a cusped curve of the type indicated in the figure. Mathematically, this curve is a *diacaustic* of the outer curve of the meniscus cross section; see [Yates 1974] for a description of diacaustics. But, as every cross section of the lens through its optical axis is identical, the locus of the viewpoints for all the light rays directed toward the center of the physical aperture is a surface of revolution of the type shown in Figure 12(b), whose every cross section is identically the diacaustic sketched in Figure 12(a). Now, if we assume that the lens below the aperture in Figure 12(a) is a typical lens, with forward and rear nodal points, then the locus of the effective viewpoints of light rays directed toward the forward nodal point of this lens after passing through the frontal meniscus will also have a shape similar to that illustrated in Figure 12(b). Further, although not all

fish-eye lenses have a single outer meniscus element as in Figure 12(a), the general nature of the frontal elements of all fish-eye lenses is the same, and, hence, every fish-eye lens effectively has a continuum of viewpoints on a surface of the type shown in Figure 12(b). The distribution in space of these viewpoints would not be a cause for concern if this distribution had a small extent—say, a maximum dimension across of a small fraction of an inch. But such a small extent is not practical, as a large frontal element is necessary in a fish-eye lens to make our usable aperture size sufficiently large—the reason for this requirement being similar to that for wanting a locally flat and distant nonplanar mirror in Section 7.2. For example, in a well-known fish-eye lens, whose angular field of view of 220°, the outer diameter of the lens is 9.3 inches [Nikon 1995].

Thus, we see that the fundamental problems with using fish-eye lenses are similar to those with using nonplanar mirrors, which we discussed in Section 7.2: one, the lack of a single viewpoint, and, two, a limit on the maximum usable aperture size without resorting to a large frontal lens element. Further, the limits on the resolution of a single captured image described in Section 7.2 also hold here, and the useful portion of a captured image might typically be limited to the periphery of the image.

Fish-eye lenses get their name from their origin, which lies in an attempt by Wood [Wood 1906] to duplicate the monocular view of a fish of the world above water from below its surface. This view encompasses the complete hemisphere bounded below by the water surface. See [Wood 1906] for several interesting fish-eye views. From Wood's original idea, two lens designs followed: the first by Bond [Bond 1922], and the second by Hill (see [Hill 1924] or [Beck 1925]). Hill's design, on which Figure 12(a) is based, is the forerunner of currently prevalent designs, such as the one described in [Miyamoto 1964].

So far, we have discussed only the fish-eye lens itself. Now, let us turn to reports of the creation and use of omni-directional views provided by such lenses. Amazingly, Hill [Hill 1924] not only proposed a lens design, but also realized and described the use of such a lens first to capture highly distorted fish-eye images, and then to provide a host of user-chosen undistorted narrow-angle images of the original scene from each fish-eye image. More recently, Lippman [Lippman 1980] reported using an interesting variation of a fish-eye lens that deemphasized the central portion of its field of view to devote a larger fraction of its image to the periphery of its field of view; Lippman also reported using a conical mirror, interestingly not to capture an omni-directional image, but to display it. Two other interesting and relevant lenses I would like to bring

to your attention here are the Sutton lens (see [Kingslake 1989]) and a nameless lens that I have seen mentioned and diagramed only in [Focal 1969] under the topic *Panoramic Camera*. The use of a fish-eye lens for omni-directional imaging has also been reported in [Ripley 1989] and [Oh and Hall 1987]. Only the last effort, of all I have mentioned, uses an electronic camera for imaging, rather than film, and, not surprisingly, the aim of this effort was to acquire some useful data for robotic tasks, rather than to produce images with adequate quality for human viewing. Finally, I mention that there is a well-known commercial product based on this approach to omni-directional imaging (see [Greene and Heckbert 1986]), this commercial product using film that has a larger-than-normal format for reasons we discussed in Section 7.2.

8. Practice

Our discussion of my design in Section 6 was primarily conceptual. However, to turn concept into reality, we must address several practical issues. Let us make these issues, then, our first order of business here. Then, we shall turn our attention to an implementation of my design.

The first issue we shall address here is this: What about the seams of the mirrored pyramid? That is, given that the edges of the mirrored pyramid have nonzero thickness, the images from neighboring cameras shall exhibit some artifacts at their common boundaries, and the question is this: Given these image artifacts at the shared image boundaries, how do we composite the individual images into a single visually seamless omni-directional image. The next issue we shall address is the effect of using cameras with lenses that have non-pinhole apertures, instead of using cameras with pinholes, on which we based our design. As we shall see, the two preceding issues are interrelated. Next, we shall discuss the calibration of the geometry, radiometry, and colorimetry of each camera. Such calibration is essential whenever we seek to combine images from multiple cameras into a single coherent image. Having attended to camera calibration, we shall address some miscellaneous practical issues that deserve mention even though they are relatively minor. Finally, I shall describe a first-cut implementation of my design, providing images to illustrate the performance of this implementation.

Throughout our discussion here, without any loss of generality, we shall limit ourselves to the geometry of Figure 9, assuming a right regular mirrored pyramid with a square base and four isosceles sides, each of these sides at 45° to the horizontal.

8.1 Pyramid Seams

Figure 13(a) illustrates the particular horizontal cross section of the mirrored pyramid in Figure 9 that contains the mirror images of the four pinholes. As exaggerated in the figure, in practice, this cross section will have non-pointed corners, these corners lying along the seams of the pyramid in three-dimensional space. Now, a simple strategy we can adopt to avoid viewing the world off the pyramid seams completely is to raise all the actual pinholes simultaneously slightly above their theoretically desirable position we discussed in Section 6. If we do so, the horizontal cross section of the pyramid that contains the mirror reflections of the pinholes shall remain the same as before, but the locations of the mirror images of the pinholes shall no longer be coincident. Rather, they shall be at the corners of a square, as illustrated in Figure 13(b), half the diagonal of this square being equal to the distance by which we raised the pinholes. Thus, we can easily make this square large enough such that each individual camera's useful horizontal field of view off the mirrored pyramid is 90°, excluding the pyramid seams altogether, the four horizontal fields adding up to 360°, as we desire.

For the geometry of Figure 9, then, we shall have four images that are uncorrupted by boundary artifacts possibly requiring complex postprocessing. We shall pay a dual price for these uncorrupted images: One, we shall not have an omni-directional view from a single viewpoint, and, two, we shall not see the world within two orthogonal sheets, each of whose thickness is of the order of the thickness of the pyramid seams we are avoiding. We are assuming pinhole apertures here implicitly, variation from which we shall address in Section 8.2.

At this point, you might think, “Well, so we don't have a single viewpoint after all, just as we did not have it with a fish-eye lens.” The answer is, “Yes, if we adopt the above strategy.” However, as we shall see in the next section, we are not bound to adopt this strategy. Further, note that there is a difference in the orders of magnitude of the spread of the viewpoints here and the spread of the viewpoints when we use a typical fish-eye lens: The pyramid seams can easily be made much less than a tenth of an inch thick each, whereas a fish-eye lens typically has a diameter of several inches. Thus, whereas with my design we shall be able to produce wide-angle images with effectively a pinhole perspective—which ensures, for instance, that straight lines remain straight in a planar image—with a fish-eye lens, we shall be able to provide only very narrow-angle images with effectively a pinhole perspective.

Then, the principal drawback of adopting the strategy described here to avoid the seams is that we shall not view the world within sheets each of whose thickness is of the order of the thickness of the pyramid seams. What we shall gain in return is that we shall avoid **all** image processing at the shared image boundaries. In practice, owing to our ability to make the non-visible sheets a tenth of an inch or less thick quite easily, and the highly redundant nature of most images, I do not expect these non-visible zones to pose a problem in most cases. This claim is substantiated by my experiences with the first-cut implementation I shall describe in Section 8.5.

8.2 Finite Aperture

In the discussion of my design so far, we have limited ourselves to pinhole apertures. In practice, of course, our aperture must be much larger than a pinhole and we must use a lens. Non-pinhole apertures are not necessarily a drawback for my design: They could, in fact, prove very beneficial. As we shall see now, they offer us, at least in principle, a strategy to seam together the individual images while viewing the world from a single viewpoint and without any non-visible zone within a 360° field of view, unlike the strategy of Section 8.1.

As we discussed in Section 2, lenses allow us to use non-pinhole apertures that increase the brightness of the image. Now, we already saw at the end of Section 6 and in Figure 10 that the pinhole geometry is duplicated by a lens as far as rays toward the forward nodal point of the lens are concerned. The question here is, What about other rays that enter the entrance pupil of the lens? As illustrated in Figure 14, depending on the sizes and locations of the mirror images of the entrance pupils of our camera lenses relative to the sizes and locations of our pyramid seams, our strategy of the preceding section to avoid looking at the seams would either work unchanged, or might require the cameras to be moved up slightly higher than originally planned, thus increasing the thicknesses of the non-visible sheets. This higher location would be necessary so that light off the mirrored pyramid from each viewed point can enter the complete entrance pupil, rather than reach just the forward nodal point and a part of the pupil. To give you a feel for numbers, the focal length of each of our lenses might typically be about a seventh of an inch, and the diameter of its entrance pupil, assumed circular—the ratio of this diameter to the focal length determining the image brightness—might typically be about half that, which is about a fourteenth of an inch. Then, if we assume that the entrance pupil and the forward nodal point are coplanar, to accommodate our non-pinhole apertures we would, in principle, have to

increase the thickness of each of our non-visible sheets by $1/\sqrt{2}$ times the diameter of the entrance pupil, which turns out here to be about a twentieth of an inch. Of course, we can always design or choose lenses with entrance pupils whose shapes (perhaps, elliptical) and locations (as far in front of the forward nodal point as possible) minimize the extent to which they increase the thicknesses of the non-visible sheets.

What is interesting here is that even though light from an object point might not be able to make it off the mirror to a lens's forward nodal point, light from that object point might make it through the entrance pupil anyway. Then, in principle, we could adjust the sizes, locations, and shapes of our entrance pupils relative to the forward nodal points such that even when all the forward nodal points are virtually colocated, we collect enough light from points within our formerly non-visible zones collectively in adjacent cameras so as to effectively have no non-visible zone. I believe that this can be done, but will be difficult in practice owing to the various unavoidable imperfections and variations in the reflectance and geometry of the mirrored pyramid, especially along its seams. I have not had a chance to investigate this possibility further yet. If we do succeed, the price we shall pay for the avoidance of all non-visible zones in this fashion—and for simultaneously viewing the world effectively from a single viewpoint—is that we shall now have to combine our four images along their shared boundaries to produce a composite image, rather than just slap these images together.

8.3 Camera Calibration

Recall from Section 2, that an image from a particular viewpoint is a representation of light rays toward that point, each ray with a particular orientation, brightness, and color. For our purposes, a convenient representation of such rays forming an omni-directional image is on a cylinder centered at the image's viewpoint, as shown in Figure 15. Note that, without any loss of generality, we are once again reverting to a strictly pinhole geometry for our discussion.

Now, we would like to know what is the brightness and color of each point imaged onto our imaging cylinder from the viewpoint at the cylinder's center. To do so, we need to discover where in our four images does a ray of known brightness and color and in a known direction toward our viewpoint end up being imaged, and, then, with what brightness and color. In other words, we wish to calibrate the geometry, radiometry, and colorimetry of our omni-directional camera.

One effective strategy to calibrate our omni-directional camera is to rotate the camera in small discrete equal steps about the axis of its pyramid while imaging a fixed vertical column of equispaced white dots on a black background—at each step of the rotation, locating the image positions, brightnesses, and colors of the dots. Actually, we note the brightnesses and colors of the black background too as we step along, because two observations in brightness and color space are necessary for the effective calibration of brightness and color. I illustrate this calibration procedure in Figure 16(a). (This calibration strategy of rotating the camera in small discrete steps is equivalent to, but much easier to implement than, immersing the omni-directional camera in a cylindrical arrangement of white dots on a black background, aligning the axis of the pyramid with the axis of the cylinder.) It is advantageous to actually use elliptical dots whose major axes are vertical, rather than circular dots, as then, for a given dot area, a dot will be less likely to intersect a non-visible zone at any stage of the calibration. Thus, column by column, we build up a mapping from our four images to our representational cylinder—in effect, determining the positions, brightnesses, and colors of rays through points on our representational cylinder toward its central viewpoint, as illustrated in Figure 16(b).

8.4 Miscellanea

Some miscellaneous issues remain to be addressed yet, and let us attend to them quickly before we move on to an implementation of my design.

One, each camera can potentially see itself in the mirror, as illustrated in Figure 17(a), and this limits the camera's useful field of view.

Two, if the camera's self image is not the factor limiting the camera's useful field of view, then it is the vertical extent of the accompanying mirror. For any given size of a mirrored pyramid, we can easily work out the distance of each camera—that is, of the camera's forward nodal point—from the pyramid axis that would maximize our vertical field of view. Our total horizontal field of view, of course, is fixed at 360°. Going through the exercise, which I skip here, we shall arrive at the following result: If the square base of the pyramid has sides of length 2γ and its truncated square top has sides of length 2δ, as illustrated in Figure 17(b), then, assuming that it is the extent of the mirrors that limits our cameras' fields of view, the optimum distance of each camera from the pyramid axis is mathematically $\sqrt{2\delta\gamma}$. This optimum distance does not guarantee us a field of view that is symmetrical about the optical axis of each camera if the

camera is pointed vertically upward. If we wish to maximize a symmetrical field of view while keeping our cameras pointed vertically upward, the optimum camera distance from the pyramid axis is $2/(1/\delta + 1/\gamma)$, which is the harmonic mean of δ and γ. In any event, it is clear that we must pay close attention to the usability of the vertex end of the mirrored pyramid if we wish to keep the size of the pyramid small for a given vertical field of view.

Three, our cameras can catch bright overhead or other light from beyond the edges of the mirrored pyramid, and so, in practice, it is necessary that we shade our lenses from extraneous light—just as we shade lenses in normal photography. Such shading is conveniently accomplished here by placing above the pyramid a flat piece of black cardboard that extends from the base of the pyramid without obstructing the useful fields of view of the four cameras off the mirrors, as shown in Figure 17(c).

8.5 An Implementation

A first implementation of my design is up and running. This implementation, although not optimal in any respect, provides an affirmation that my design is practical. In reality, this implementation performs much better than I anticipated: I expected a fair amount of image processing to be necessary to combine the individual images seamlessly, never anticipating that merely slapping together data from the four images would suffice for most purposes, as it seems to.

A mirrored pyramid, of the type sketched in Figure 9, was constructed. A close-up photograph of this pyramid is shown in Figure 18. The individual mirrors of the pyramid are of polished stainless steel, and the seams of the pyramid are easily each less than a millimeter thick, but I am unsure as to how accurate the various angles are. The four cameras used, all visible in Figure 18, are each a Sony XC-999 with a lens of focal length 3.5 millimeters and a nominal horizontal field of view of 100°+. As is to be expected, the lenses all exhibit noticeable barrel distortion (see [Hecht 1987]), but that is not a problem owing to our calibration of the geometries of image capture by the four cameras.

The system architecture is as in Figure 19. Each camera's NTSC output is fed to a frame grabber, currently a Snapper-24, that continuously multiplexes through its four inputs sequentially. The brightness and color of each image are corrected according to a red, a green, and a blue (RGB) look up table (LUT) determined during the calibration phase. The output of the RGB LUT is fed to a digitizer that converts its analog input to a

digital output. All the cameras and the digitizer are synchronized by an external source of synchronization (Sync). Each output image from the digitizer is read into the memory of an ordinary personal computer (PC) running a 100 MHz Pentium processor, and, then, this image is mapped onto a cylinder in accordance with the mapping determined during calibration. This cylinder onto which the four image streams are mapped independently is unwrapped and displayed on a regular monitor.

Figure 20 shows sample images before and after their mapping onto a 360° cylindrical image. Figure 20(a) shows four raw (uncorrected) images acquired by the four cameras. Figure 20(b) shows these images assembled together into a 360° view after each image has been corrected individually and independently for geometric, radiometric, and colorimetric distortions. In Figure 20(b), I have marked the boundaries of the individual images for your attention. Also, I have included in the imaged scene a meter rule that I placed less than 1 foot away from the axis of the pyramid to affirm that this design is truly capable of working at all distances, not just for objects that are far away. The camera apertures for this 360° view of my laboratory were set at f/2.0.

I show only one omni-directional image to keep my paper short, but this image is typical. Using completely off-the-shelf components, we have been able to provide a 360° x 50° panoramic-image video stream that we can display at 7.5 panoramic frames per second for a display size of 780-pixels x 130-pixels on a relatively inexpensive PC. Our frame rate is currently limited by our frame grabber, which sequences through the four input video streams. To accomplish even the current panoramic frame rate, given the processing power of a PC, we are forced to cut corners in our mapping of the four input image streams to the single output image stream in two ways. One, we map the brightnesses and colors of all pixels in an image identically (through the RGB LUT), rather than individually. Two, we perform only a closest-pixel integral approximation in our position mapping, rather than interpolate the result from the real positions of observed pixels on the representational cylinder. This integral approximation of positions results in some apparent aliasing. But, on the other hand, the image seams are typically hard to locate, as is evident from Figure 20. Typically, one has to look for the seams, often by waving an object and relying on the sequential frame capture to reveal the seams. The non-visible zones of this implementation are two orthogonal sheets, each about an eighth of an inch thick. Non-visible zones of even this thickness, which can definitely be reduced by a factor of two or more by a more careful implementation, are typically not apparent to viewers unless

specifically pointed out with the aid of a meter rule or some other such device.

9. Conclusion

I have presented here the design of what I believe is the first true omni-directional camera. A first implementation of this design suggests that it is practical. Far more sophisticated and superior implementations of this design are possible.

Further, several extensions of the design are possible. I would like to mention three. One, we could create an omni-directional projector, rather than a camera, by replacing each camera with a projector. Two, we could extend the field of view of our omni-directional viewer to encompass a view of the world above by using a hollow mirrored pyramid with an upwardly directed camera sitting within this pyramid, this camera's forward nodal point colocated with the virtual locations of the forward nodal points of the other cameras that are all outside the pyramid. Three, almost the same design as in Figure 9 can allow us to double both the horizontal and vertical resolutions of a camera. In the design of such a high-resolution viewer, we could locate four cameras as in Figure 9, but point these cameras not upward, but toward the vertex of the pyramid so as to view the world below the pyramid. Then, without getting into details, each camera would capture a quarter of the total field of view looking downward. This resolution doubling strategy of dividing a field of view into four quadrants by a mirrored pyramid can, in principle, be applied recursively.

The primary disadvantage of the omni-directional camera I have designed, as is true of alternate designs that are not motion based, is that we cannot gradually zoom the camera into a smaller portion of its field of view. In a normal camera with a zoom lens, we can gradually shrink the field of view of the camera down from its maximum size to its minimum size. In my design, however, if we use zoom lenses on the individual cameras and reduce their fields of view, we shall immediately obtain a disjointed field of view. One possible solution to this drawback is to have available at all times the maximum desired image resolution, perhaps by using an n-sided pyramid where n is large, and then provide a lower-resolution image unless the user asks to zoom in, which then would be possible computationally in a gradual fashion.

Acknowledgments

Without the assistance of Brian Schmult, I would have no implementation to show you at this time. In a span of a few months, Brian engineered the mirror assembly, configured the processing architecture, and wrote a major portion of the accompanying software.

Much of the relevant literature was brought to my attention by others after I began demonstrating the implementation I outlined. Bill Ninke led me to discover the patent by Judd and Smoot that proposes the use of planar mirrors to improve camera resolution. Frank Pirz pointed me to the use of fish-eye lenses for omni-directional electronic imaging, and Freddy Bruckstein pointed me to the use of conical mirrors for the same purpose. Dick Kollarits pointed me to several sources of information on lenses. Kevin Chen brought the article by Halfhill in *Byte* to my attention. Ingrid Carlbom pointed me to the papers by Chen and by McMillan and Bishop in *SIGGRAPH 95*. Mike Naimark brought the book by Meehan to my attention.

Again, after I had a working prototype, several individuals provided useful technical input. Paul Henry corrected a misconception I harbored about the effect of mirror reflection on scene brightness early on, and later suggested several improvements to a draft of this paper. Andy Lippman and Mike Naimark shared with me their experiences with fish-eye lenses for omni-directional viewing. John Denker pointed out to me first that non-pinhole camera apertures could possibly eliminate the non-visible zones extending from the seams of my design.

Finally, I acknowledge with great pleasure the support I received at Bell Laboratories from Paul Henry and Arun Netravali to pursue my ideas unhindered.

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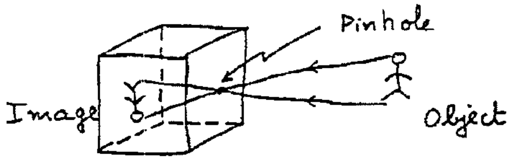

Figure 1 Pinhole camera.

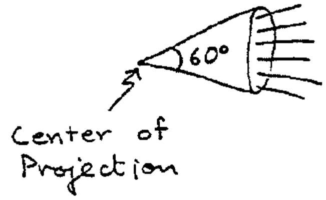

Figure 4(a) Typical camera's field of view.

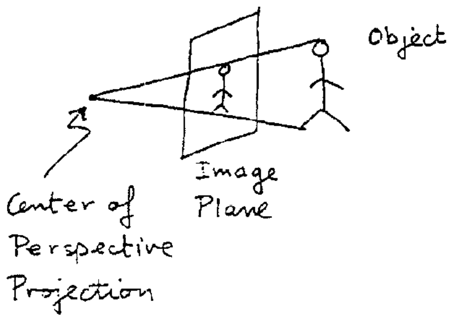

Figure 2 Perspective Projection.

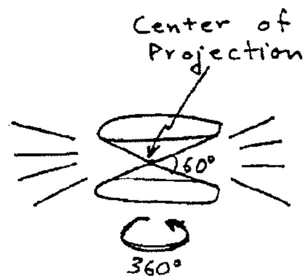

Figure 4(b) Omni-directional camera's field of view.

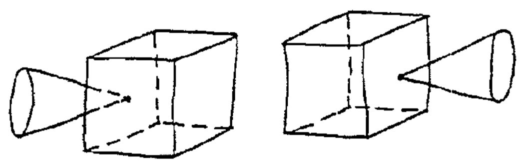

Figure 5 The problem: We must colocate multiple pinholes.

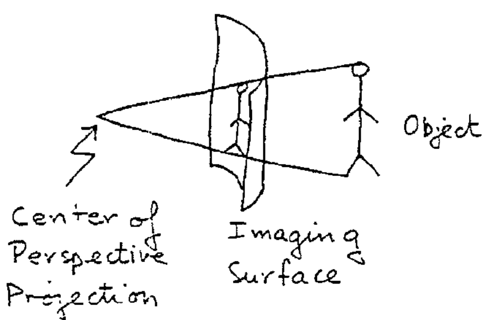

Figure 3 Perspective projection onto a nonplanar surface.

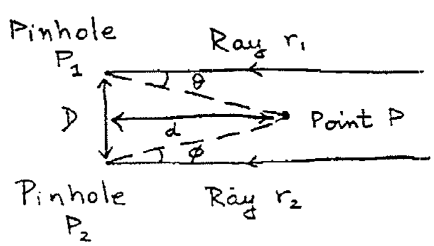

Figure 6 Geometry to compute angular disparity between two pinhole-camera images.

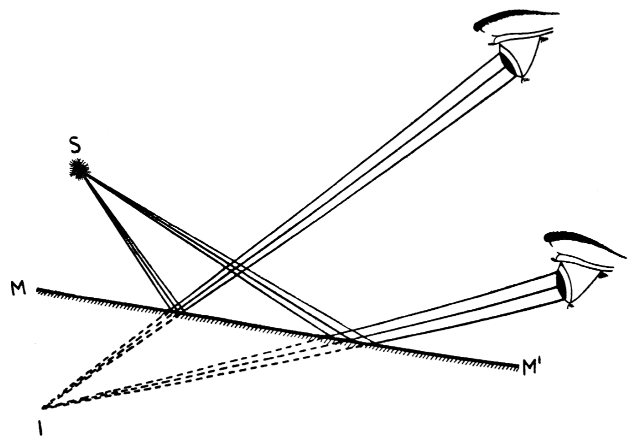

Figure 7 Reflection in a planar mirror, as explained by Kepler (after [Ronchi 1957]).

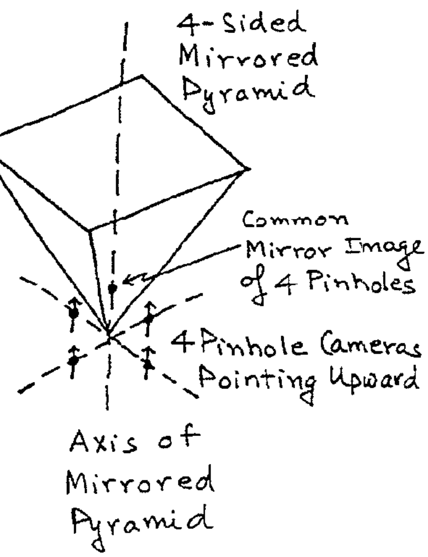

Figure 9 Design of an omni-directional camera.

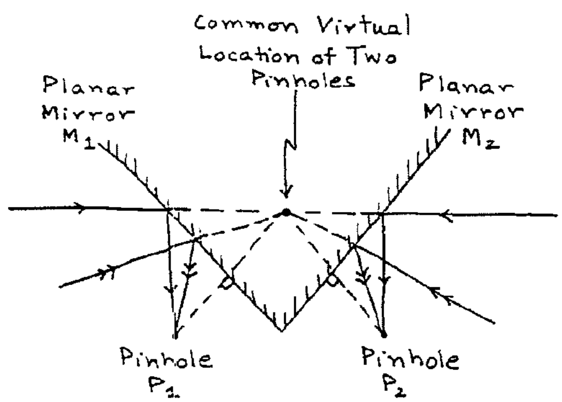

Figure 8 Colocation of two pinholes by two planar mirrors.

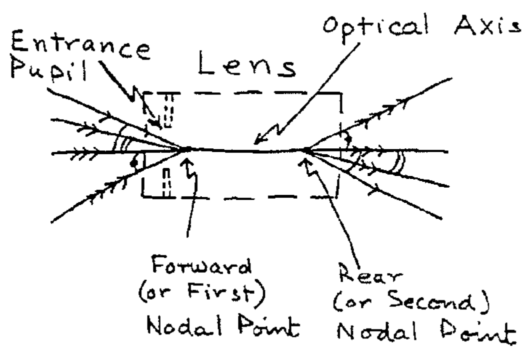

Figure 10 Forward and rear nodal points.

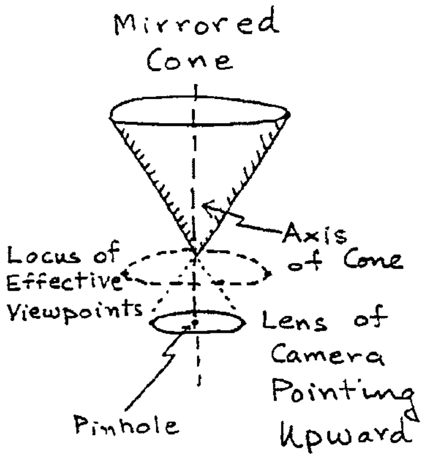

Figure 11 Omni-directional camera using a mirrored cone.

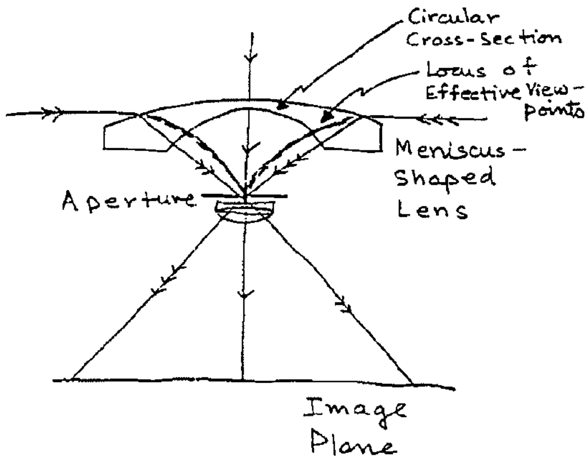

Figure 12(a) Typical fish-eye lens (after [Hill 1924]).

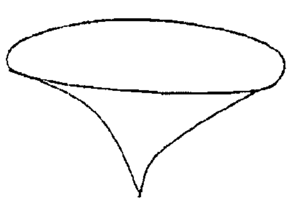

Figure 12(b) Typical locus of effective viewpoints of a fish-eye lens.

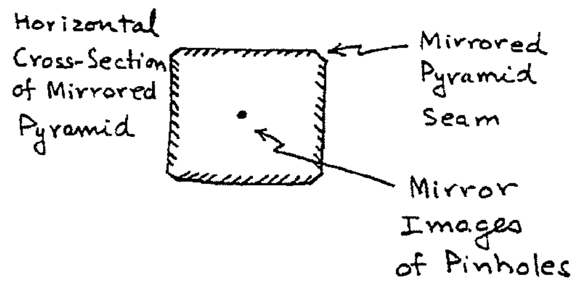

Figure 13(a) Colocated mirror images of pinholes.

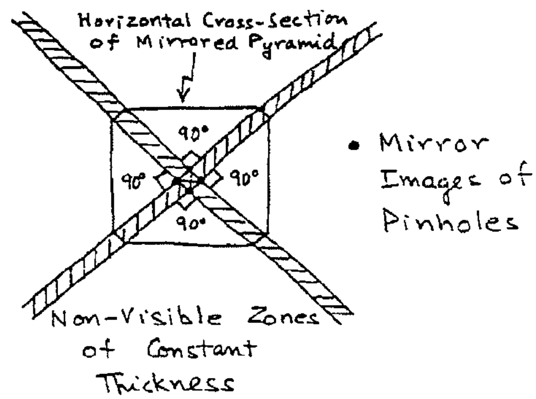

Figure 13(b) Displaced mirror images of pinholes.

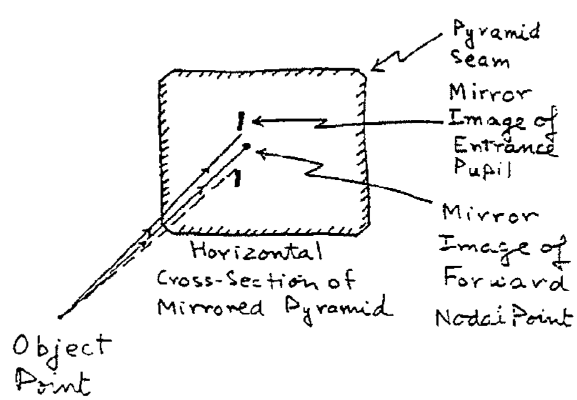

Figure 14 Role of finite aperture in avoidance of pyramid seams.

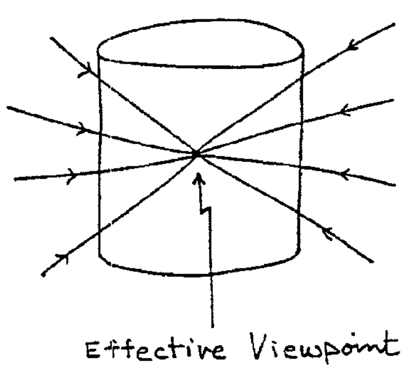

Figure 15 Cylindrical representation of omni-directional image.

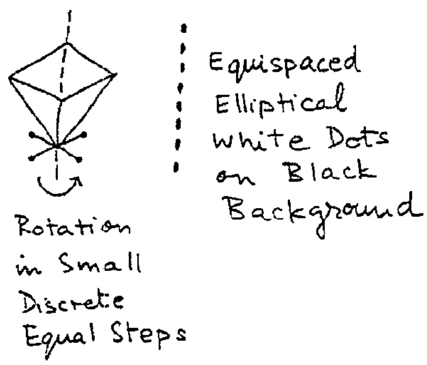

Figure 16(a) Calibration procedure.

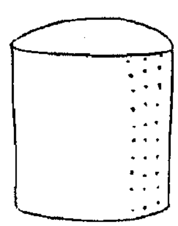

Figure 16(b) Column by column build up of mapping to representational cylinder.

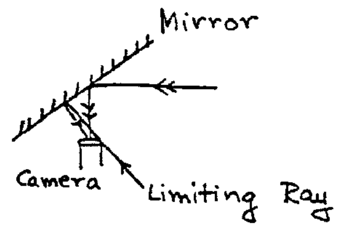

Figure 17(a) Camera's self image limits its field of view.

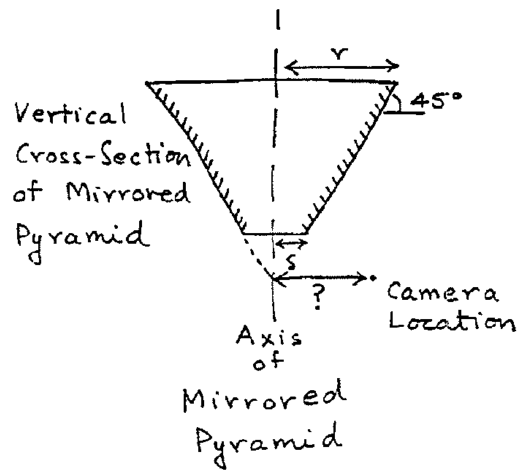

Figure 17(b) Geometry to compute location of camera that maximizes its vertical field of view.

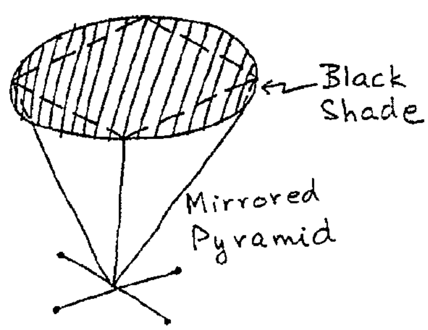

Figure 17(c) Camera shade to block extraneous light.

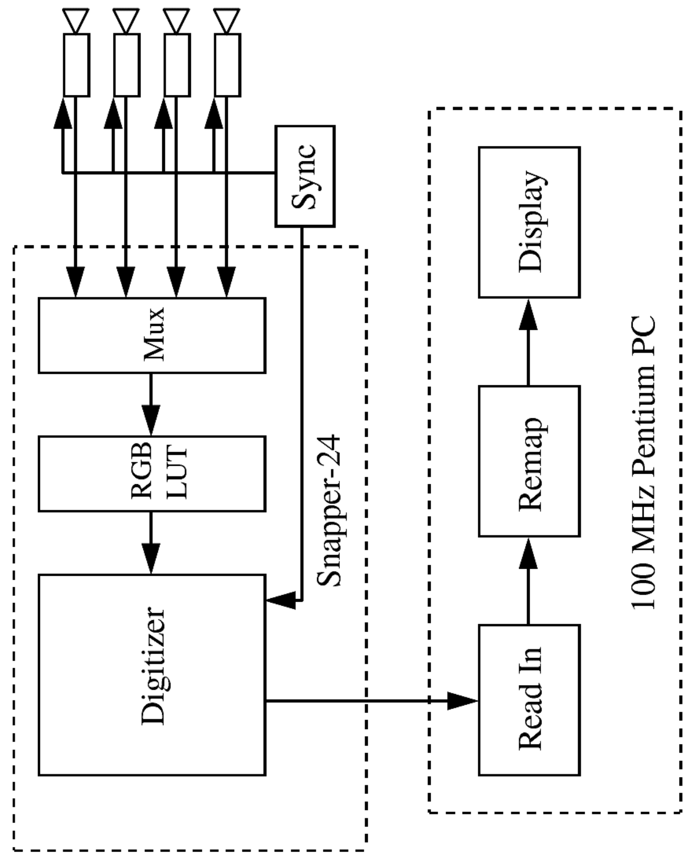

Figure 19 Implemented system architecture.

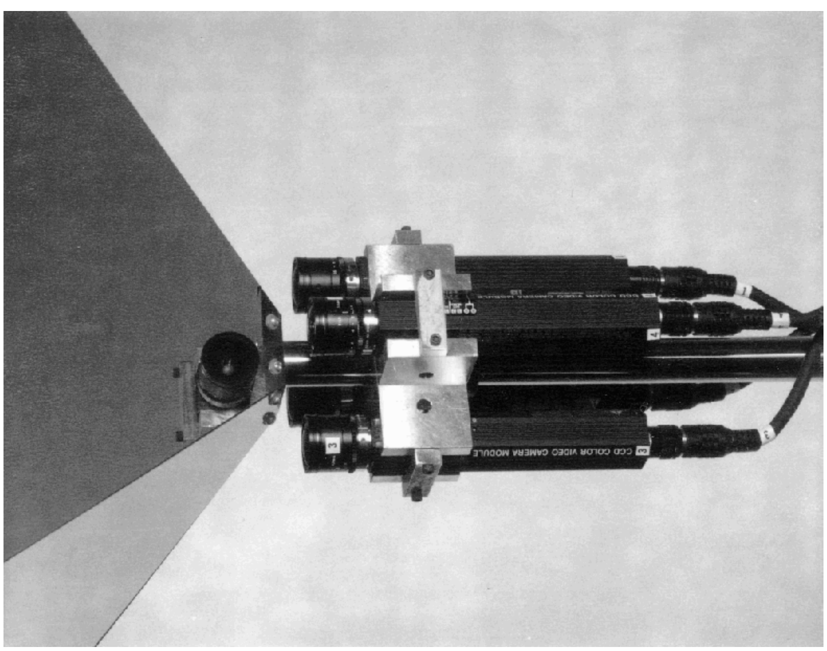

Figure 18 Photograph of implemented mirrored pyramid with attached CCD cameras.

Figure 20(a) Raw uncorrected images.

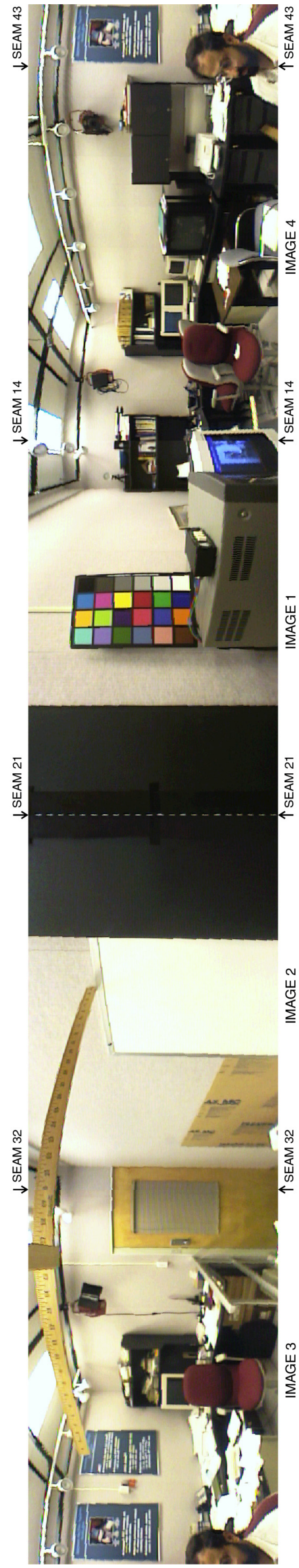

Figure 20(b) Omni-directional 360° cylindrical image unwrapped.

EXHIBIT B

"Generation of High-resolution Stereo Panoramic Images by Omnidirectional Imaging Sensor Using Hexagonal Pyramidal Mirrors,"

Kawanishi, T., Yamazawa, K., Iwasa, H., Takemura, H., and Yokoya, N.,

ICPR, vol. 1, pp. 485-489,

August 16-20, 1998

("Yamazawa 1998")

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Generation of High-resolution Stereo Panoramic Images by Omnidirectional Imaging Sensor Using Hexagonal Pyramidal Mirrors

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Abstract

We have developed a high-resolution omnidirectional stereo imaging sensor that can take images at video-rate. The sensor system takes an omnidirectional view by a component constructed of six cameras and a hexagonal pyramidal mirror, and acquires stereo views by symmetrically connecting two sensor components. This paper describes a method of generating stereo panoramic images by using our sensor. First, the sensor system is calibrated; that is, twelve cameras are correctly aligned with pyramidal mirrors and the Tsai's method restores the radial distortion of each camera image. Stereo panoramic images are then computed by registering the camera images captured at the same time.

1. Introduction

Reality and presence are very important factors of visual communication systems. Many virtual reality systems have realized these factors by using 3D computer graphics or real scenes. A new approach called "Mixed Reality" has been recently suggested, which combines computer graphics images with real scene images to realize more real and present virtual environment. Many mixed reality systems use a standard video camera, which is not sufficient for realizing seamless fusion between the virtual environment and the real scene. The images captured for mixed reality systems must be wide, dynamic and clear. In addition, the distance information around the surroundings is also needed for the compositiun with 3D computer graphics and for the generation of binocular disparity. Therefore. the sensor needs the following four features: omnidirectional, video-rate, high-resolution and stereo.

Our objective is to develop an image acquisition system for mixed reality with the four features above. This paper describes the construction of an omnidirectional stereo imaging sensor system and methods to calibrate our sensor and to generate stereo panoramic images. The sensor system takes an umnidirectional view by a component constructed of six cameras and a hexagonal mirror and consists of symmetrically connected two sensor components to get stereoscopic views. Six cameras and the hexagonal mirror are arranged su that six cameras virtually have a fixed view point. The sensor system is calibrated; that is, twelve cameras are correctly aligned with pyramidal mirrors and radial distortion of each camera image is restored by using Tsai's method. Stereo panoramic images are then computed by projecting registered camera images onto a pair of cylindrical surface. Finally, the experiment results are described by showing computed omnidirectional stereo panoramic images.

2. Previous Work

The early designers of VR systems used a regular camera to capture an image a movie. The camera has too narrow view to capture images for the mixed reality. Then the wide view systems have been developed and they often have an omnidirectional view. Methods to acquire omnidirectional views are typically classified into the two categories: the methods to gather multiple images to generate an omni directional image and the methods to capture an omnidirectional image at once. In addition, they are classified into two categories by the viewpoint of the image: a single viewpoint and multiple viewpoints. The images captured at the same viewpoint are continuous. The images captured at multiple viewpoints cause discontinuity and occlusion among the images at the different viewpoints. On the other hand, it has much more limitation and difficulty to acquire an image from the same viewpoint than to combine images at multiple viewpoints into a single omnidirectional image. The system with multiple images and multiple viewpoints is relatively easy to construct. The system gathers multiple images captured by a regular camera and combines them into omnidirectional image. Such a system is adopted by Quick Time VR system[1] and has many market applications. However, the images generated by such a system are not always continuous and consistent, nur can capture the dynamic scene at video-rate.

One example of the system with multiple images and a single viewpoint is a rotating camera system[2]. In such a system, the camera rotates around the center of the lens. It generates an omnidirectional image from a single

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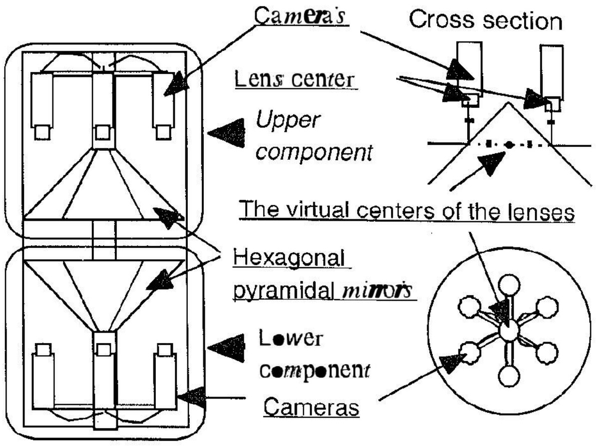

Figure 1. Construction of omnidirectional stereo imaging sensor

viewpoint. Howeve, it is difficult to acquie an omnidiectional image of a dynamic scene at video-ate by using a otating camea.

The existing methods that can captue an omnidirectional image at once use a fish-eye lens[3] or a spheical mior. Most of the systems of this type ae not pespective and do not satisfy the single viewpoint constaints. The systems with vey expensive fish-eye lens and those with a hypeboloidal[4] or a paaboloidal[5] mior satisfy the pespective chaacteistics and the single viewpoint constaint. Howeve, these single image systems have difficulty in obtaining high-esolution images. Now the sensor for endeing and modeling the dynamic eal scene for mixed eality is expected to satisfy the following thee featues: (1) an omnidiectional pespective view fom a single viewpoint, (2) imaging at video-ate and (3) high-esolution imaging. In addition, (4) a steeoscopic view is needed for obtaining 3D infomation aound the suoundings.

3. Constitution of Omnidirectional Sensor

To oveome the poblems with conventional methods, we popose a new appoach to satisfy our four equiements. Fist, we popose an image sensor that is composed of six cameas and a hexagonal pyamidal

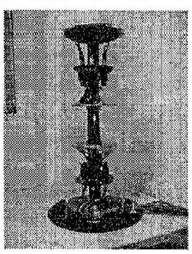

Figure 2. Omni-directional stereo imaging sensor

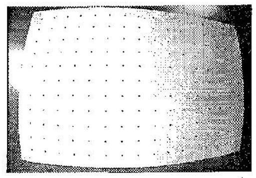

Figure 3. Calibration pattern

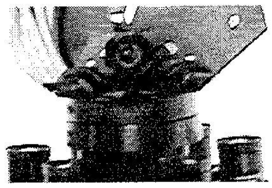

Figure 4. The virtual same lens on the edge

mior. The sensor is designed so that the vitual lens centes of six cameas ae located at a fixed point in the mior images. The sensor can take an omnidiectional image fom a single viewpoint. In our system, two symmetical sets of the component ae used for a steeo omnidiectional imaging. The design of this sensor is shown in Figue 1. Each camea is a egular one and has the wide-angle lens. The figue of the mior is an equilateal hexagonal pyamid. The top of the mior faces the six cameas and the base plane of the mior is placed on a pependicular to the line of sight of the camea. The sensor popely aanged captues images of eal scenes though the eflection on a pyamidal mior. Figue 2 shows a photogaph of the sensor

4. Sensor Calibration

In oder to compose an omnidiectional image fom a single viewpoint by using the sensor poposed, the cameas of the sensor must be aanged at ight positions against the mior as shown in the pevious section. In addition, as six cameas ae designed to acquie an omnidiectional view, the viewing angle of each camea is set to be vey wide (moe than 60 degees hoizontally). By using wide-angle lenses, the captued images tend to have distotions. Theefoe, the distotion compensation must be caied out.

Estimation of the distortion parameter

The sensor is calibated by Tsai's calibation method[6]. Tsai's method estimates the intenal paametes and the extenal paametes fom the intinsic paametes and the coespondence between 3-D points in the eal scene and 2-D points in the captured image. The main advantages of Tsai method ae that the model has only two assumptions: a pinhole camea model and a adial distotion model and that the code of the Tsai's method is open to the public.

The conversion from distorted image to undistorted image needs some of the intenal paametes: the optical center and the coefficients of distotion. These paametes ae calculated by Tsai's method with the calibation patten shown in Figue. 3, which consists of a gid of black dots placed evey 34x28 mm and the size is on a 476x280mm board.

Arrangement of the cameras

Six cameas must be aligned to get an omnidiectional image fom a single viewpoint. The aangement of the cameas is impotant because an omnidiectional image

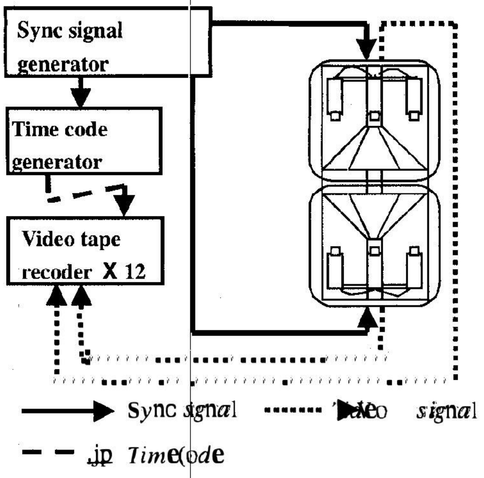

Figure 5. Omni-directional stereo panoramic image acquisition system

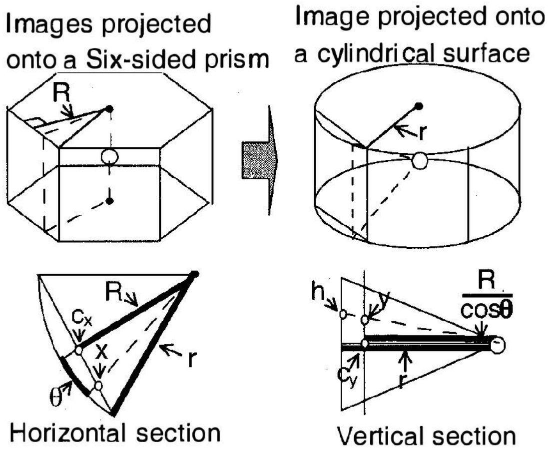

Figure 6. Transformation of captured images to a stereo panoramic image

generated from multiple viewpoints has discontinuity at the gap between images captured by different cameras. In order to set each viewpoint located at the same position, we arranged the cameras by the following three criteria;

1) the overlapping of the centers of the lenses of cameras on the edge of the mirror,
2) the correspondence with the position and the size of mirror region on the image plane at each camera and
3) the continuity of two adjacent images.

The first criterion means that, on the right arrangement,

R: the focal length (pixel)
r: the radical length of generated panoramic image
$c_x c_y$: the position of center of lenses on the images

the image of camera lenses observed on the edge of the mirror should look like a single lens, as the image corresponds to a virtual single viewpoint in the mirror image. Each pair of the lenses of the cameras located next to each other is properly adjusted to overlap. This overlap makes the virtual centers of the cameras placed at the same point. In addition, the viewing directions of the cameras can properly be adjusted. Figure 4 shows the overlap of the lenses.

Second, a fine adjustment of the positions and the directions of the cameras and the mirror is carried out. The positions and the directions of camera are so arranged that the mirror-imaging region on the camera image is to be the same positions and have the same size. The positions of the mirror region in the captured image indicate the direction of the optical axis, and the size of the mirror region indicates the height of the camera against the mirror. This adjustment can realize finer arrangement of the cameras against the mirror.

The correctness of the camera alignment is finally evaluated by continuity of two adjacent images. When the cameras are properly placed, there are no overlapping areas in two adjacent images. In addition, it is so adjusted that epipolar lines correspond in the upper component and the lower component for stereoscopic imaging.

5. Generation of Stereo Panoramic image

This section first shows a system for images capturing. Then, described is the method for generating stereo panoramic images from image sequences captured by the sensor.

Generating a stereo panoramic image

Stereo panoramic images are generated from twelve images captured by twelve cameras. It is required that twelve images are captured at the same time. Our system is designed that the twelve cameras are gen-locked by the same sync signal and capture images at the same timing. The time code is used to identify frames in image sequences. The generated time code is fed into each videotape recorder. A VTR records an image and a time code to the videotape at every frame. The overview of this system is shown in Figure 5.

Synchronized image sequence acquisition system

An omnidirectional panoramic image is generated from six sheets of images respectively acquired by the upper sensor or the lower sensor at the same time. Six sheets of images correspond to an omnidirectional image onto a six-sided prism. Figure 6 shows the transformation from an image on a six-sided prism to an image on a cylindrical surface. The transformation is acquired from the correspondence between the point (r,?? on a panoramic image and the point (x, y) on six sheets of acquired images. The transformation is described by Equation (1).

$$x = c_x + R \cdot \tan\theta$$

$$y = c_y + \frac{h \cdot R}{r \cdot \cos\theta} \qquad (1)$$

The parameters of each camera consist of the projective

Figure 7. Images captured at the same time and an omnidirectional stereo panoramic image generated from them

center (ex, cy) in the image and the focal distance (R). These parameters are heuristically found by the continuity of the image and the epipolar constraints. Figure 7 shows images captured by all the cameras onto the six-sided prisms and generated omnidirectional panoramic images.

Generating stereo panoramic image sequences

If the parameters are once decided for generating a pair of stereo omnidirectional images, the omnidirectional stereo image sequence can be generated by using the same parameters. The movies recorded in the videotape by each camera are captured and stored as still images with a time-code at every frame. After all the movies are taken in from the videotape of each camera, the stereo panoramic image is computed from 12 sheets of the still images. The repetition of this treatment at every frame forms an omnidirectional stereo panoramic movie.

6.jp Experiment

Experiment were carried out with images captured for three seconds where the system was fixed and some objects were moving (here, four people move). Images are captured at video-rate (30 frame/second), and 90 sheets of omnidirectional stereo panoramic images for 3 seconds are generated.

Figure 8, Figure 9, and Figure 10 show omnidirectional stereo panoramic images at O-second, 1.5-second and 3-second respectively. The vertical deviation at the gap between the adjacent images is a little and the horizontal deviation between the upper image and lower image exists about a few pixels. This deviation must be removed for stereo matching using the epipolar constraints. Moreover, a color is a little different between the adjacent images, and the compensation should further be investigated.

7.jp Conclusion

This paper first describes the calibration of an omnidirectional stereo panoramic imaging sensor designed for imaging dynamic environments. Next, described is the way to generate an omnidirectional stereo panoramic image from acquired images. The images that were actually generated were shown. Omnidirectional highresolution images from a single viewpoint can be acquired by the sensor. A stereo imaging can moreover be done.

The present system has some problems: color adjustment is not complete; there is a limit in the precision of the calibration because of adjustment by the hand operation. After the problems above are solved, vertical disparities will be changed into horizontal disparities to project generated movies to a display device of a devotion type like head-mounted display (u · D).jp Moreover, the sensor will be mounted on vehicles for imaging a dynamic scene in the wide area (streets).

Acknowledgement

This work was supported in part by the

Telecommunications Advancement Organization of Japan and also by Grant-in-Aid for Scientific Research under Grant No.09555127 and 09780385 from the Ministry of Education, Science, Sports and Culture.

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[5] V.N. Peri and S.K. Nayar. Generation of perspective and panoramic video from omnidirectional video. *Proc. Image Understanding Workshop*: 243-245, May 1997

[6] Roger Y. Tsai. A versatile camera calibration technique for high accuracy 3D machine vision metrology using off-the shelf tv cameras and lenses. *IEEE Journal of Robotics and Automation*, RA-3(4): August 1987.

[7] V. Nalwa. A true omnidirectional viewer. Tech Report of Bell Laboratories 1996

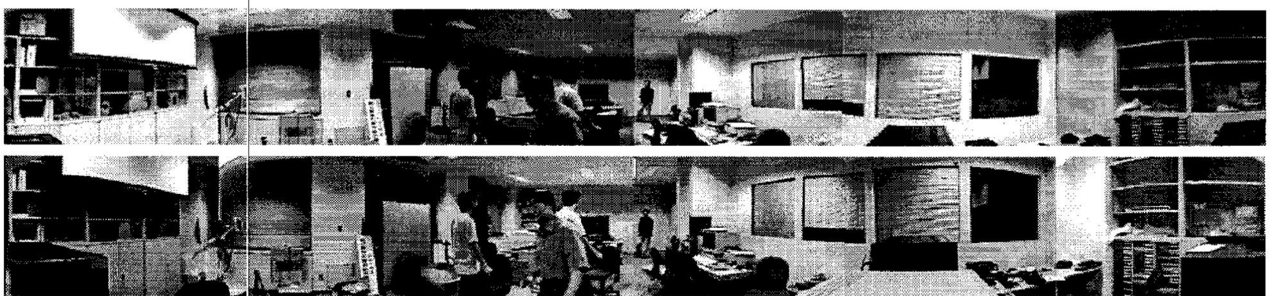

Figure 8. Omnidirectional stereo panoramic image (0.0sec)

Figure 9. Omnidirectional stereo panoramic image (1.5sec)

Figure 10. Omnidirectional stereo panoramic image (3.0sec)

EXHIBIT C

Yamazawa 1998 References as described
on the publisher IEEE's website

Reference 7 is to Nalwa 1996

Generation of high-resolution stereo panoramic images by omnidirectional imaging sensor using hexagonal pyramidal mirrors

Publisher: IEEE

T. Kawanishi ; K. Yamazawa ; H. Iwasa ; H. Takemura ; N. Yokoya **All Authors**

Abstract: We have developed a high-resolution omnidirectional stereo imaging sensor that can take images at video-rate. The sensor system takes an omnidirectional view by a compone... **View more**

Metadata

Abstract:
We have developed a high-resolution omnidirectional stereo imaging sensor that can take images at video-rate. The sensor system takes an omnidirectional view by a component constructed of six cameras and a hexagonal pyramidal mirror and acquires stereo views by symmetrically connecting two sensor components. The paper describes a method of generating stereo panoramic images by using our sensor. First, the sensor system is calibrated; that is, twelve cameras are correctly aligned with pyramidal mirrors and the Tsai's method restores the radial distortion of each camera image. Stereo panoramic images are then computed by registering the camera images captured at the same time.

Published in: Proceedings. Fourteenth International Conference on Pattern Recognition (Cat. No.98EX170)

Date of Conference: 20-20 Aug. 1998

Date Added to IEEE *Xplore*: 06 August 2002

Print ISBN:0-8186-8512-3

Print ISSN: 1051-4651

INSPEC Accession Number: 6103981

DOI: 10.1109/ICPR.1998.711187

Publisher: IEEE

Conference Location: Brisbane, QLD, Australia

References is not available for this document.

Authors

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Citation Map

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Google Scholar

Citations

Keywords

Metrics

EXHIBIT D:

FullView's Response to Polycom's First Set of Interrogatories

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UNITED STATES DISTRICT COURT

FOR THE NORTHERN DISTRICT OF CALIFORNIA

FULLVIEW, INC., a Delaware corporation,

Plaintiff,

vs.

POLYCOM, INC., a California corporation,

Defendant.

Case No. 3:18-cv-00510 EMC

PLAINTIFF FULLVIEW, INC.'S OBJECTIONS AND RESPONSES TO DEFENDANT POLYCOM, INC.'S FIRST SET OF INTERROGATORIES

Plaintiff FullView, Inc. ("FullView" or "Plaintiff"), hereby provides the following objections and responses to Defendant Polycom Inc.'s First Set of Interrogatories.

GENERAL OBJECTIONS

The following General Objections apply to each of the interrogatories whether or not specifically objected to and/or incorporated into each response:

1. As of the date hereof, Plaintiff has not yet had a sufficient opportunity to discover or otherwise obtain and review all information, materials, and documents that may have some bearing on this case. Consequently, these responses are based only upon such information, materials and documents currently available, known to, or understood by Plaintiff. As this action proceeds, Plaintiff anticipates that further discovery, research, and analysis may supply additional facts and additional meaning to the known facts. Plaintiff reserves its right to use, as evidence in this action, any hereafter-acquired or discovered information that would have been responsive to these interrogatories.

2. Plaintiff will make reasonable efforts to respond to every interrogatory, to the extent it has not been objected to, as Plaintiff understands and interprets the interrogatory, provided that the interrogatory is not so vague and ambiguous that a response is impossible. If Defendant subsequently asserts an interpretation of the interrogatory which differs from that of Plaintiff, Plaintiff reserves its right to supplement its objections and responses as necessary.

3. These responses are not in any way to be deemed an admission or representation that there are no further facts, documents or witnesses having knowledge relevant to the subject matter of these interrogatories.

4. Plaintiff objects to these interrogatories to the extent that any interrogatory seeks information that is protected from discovery by the attorney-client privilege, the attorney work-product doctrine, or any other applicable privilege or doctrine. Plaintiff will not disclose any such protected information in response to these interrogatories.

5. Plaintiff also objects to these interrogatories to the extent that they are prematurely directed to matters of law, rather than of fact, before factual discovery is complete.

6. Plaintiff objects to each interrogatory to the extent that it seeks the premature disclosure of expert opinions or analysis.

7. Plaintiff's responses are made solely for the purposes of this action. No incidental or implied admissions are intended by these responses.

8. Plaintiff objects to the interrogatories in their entirety to the extent that they purport to impose obligations on Plaintiff beyond those set forth in the Federal Rules of Civil Procedure and Rules of Court.

9. With respect to any interrogatory to which Plaintiff responds, Plaintiff does not concede the relevance or materiality of the interrogatory or the subject matter to which it relates. These responses are given subject to correction of any omissions or errors made by Plaintiff and without in any way waiving or intending to waive:

a. Any objections as to competency, materiality, privilege, relevancy, propriety, admissibility and/or any other objections on grounds which would require exclusion of any information contained herein;

b. The right to object to other discovery proceedings involving or relating to the same subject matter as the interrogatories; or

c. The right at any time to revise, correct, add to, or clarify any of the responses set forth herein.

10. Plaintiff objects to these interrogatories, and to the definitions contained therein, to the extent that they call for the disclosure of confidential, private, proprietary and/or trade secret information.

11. Plaintiff's responses are made subject to these General Objections as set forth above and the specific objections set forth below, and Plaintiff specifically reserves the right to reassert any objection by motion or at the time of trial.

SPECIFIC OBJECTIONS AND RESPONSES

INTERROGATORY NO. 1:

For each asserted claim of the Patent-in-Suit, describe in full detail the facts and circumstances surrounding the alleged conception and actual reduction to practice (if any) of the claimed subject matter. This description should include without limitation the earliest claimed priority date for each asserted claim, the alleged dates and locations of any such conception and reduction to practice, including any acts of diligence, the identity of individual(s) involved and each of their respective roles, and the identity by Bates number of any documents (including but not limited to all communications, notes, memoranda, and invention disclosure forms) that describe the foregoing.

RESPONSE TO INTERROGATORY NO. 1:

All inventions were conceived and reduced to practice at Bell Laboratories, Holmdel, NJ 07733, by Dr. Vishvjit S. Nalwa. The original camera was conceived in January 1995, the first patents on the inventions directed to it were filed in April of that year and it was reduced to practice around August of that year (FULLVIEW002132–37, 2004–34). This original implementation was subsequently put on display in the lobby of Bell Labs at Murray Hill, NJ, where it was photographed by the inventor in April 2009 (FULLVIEW002138).

One drawback of the original 1995 design, with the pyramid's apex below the pyramid's base, was lens flare caused by overhead lights shining directly onto camera lenses. A shade above the pyramid's base would partially limit this flare, but a more robust solution was to turn the complete device upside down so that the pyramid's base is above its apex, rather than below. This invention was conceived around 1996-1997 and was grouped into a single patent with the inventions that claimed nested and back-to-back pyramids. Each of these inventions is facilitated by the "support member" of claims 10-12. A drawing of the claimed nested and back-to-back pyramid configurations from September 23, 1997 (FULLVIEW0020~~0~~35) indicates that the invention of the asserted claims was communicated before that date to the patent attorney who filed the patent application. The asserted claims were reduced to practice in 1999-2000: A product

that implemented these claims was sold to USC around May 2000. The priority date claimed for each asserted claim is the patent's filing date of August 28, 1998.

There was thorough diligence by the inventor over 1995-1998 and beyond, especially after it became clear that the invention would be commercialized, including a thorough search of the literature and of patent databases. In addition, and in particular, every pointer to related art provided to the inventor by those who saw a prototype of the invention or read the technical memorandum that described it (FULLVIEW002004-34), was investigated. Thousands of individuals worldwide became aware of the invention in that period, several traveling to Holmdel, including from the San Francisco Bay Area and later from Japan and Germany, to meet with the inventor and seek business arrangements with him and his employer. Many experts in the field well-known to the inventor communicated their knowledge of related art to him. Every art with a bearing on the patent application for the '143 Patent that came to the attention of the inventor or his patent attorneys was disclosed to the patent office until the last related patent (the '711 Patent) was granted in 2004.

INTERROGATORY NO. 2:

For each asserted claim of the Patent-in-Suit, describe in detail the complete factual and legal bases for Plaintiff's contention(s) that the Patent-in-Suit is not invalid under 35 U.S.C. §§ 102, 103, and/or 112, including by specifically responding to each ground of invalidity in any invalidity contentions served by Polycom; identify by Bates number all documents concerning the foregoing; and identify the individual(s) (at or employed by Plaintiff or under Plaintiff's control) most knowledgeable about the foregoing.

RESPONSE TO INTERROGATORY NO. 2:

Plaintiff objects to this interrogatory on the ground that it is premature. Among other things, related discovery is not complete. The contentions Polycom seeks here are not required by the Northern District Local Patent Rules and will be provided in the process of the parties' competing summary judgment motions that the parties anticipate.

Moreover, there is no 35 U.S.C. § 112 contention in Polycom's invalidity contentions and preliminary responses to 35 U.S.C. §§ 102, 103 contentions were provided in FullView's Preliminary Response and other filings presented in the IPR Proceedings. FullView presently sees no substantive difference between Polycom's invalidity contentions in this case and the assertions that Polycom presented in its IPR Petition. A more complete response to Polycom's invalidity contentions shall be forthcoming in the Plaintiff's expert witness declaration and subsequent motion for summary judgment.

INTERROGATORY NO. 3:

If Plaintiff contends that any secondary considerations (or objective indicia) support their contention(s) that the Patent-in-Suit is not invalid, describe in detail which, if any, purported secondary considerations (or objective indicia) (including but not limited to commercial success, long-felt need, prior failure of others, unexpected results, industry recognition, and copying) you intend to rely on to support the contention that the Patent-In-Suit is not invalid; describe in detail the factual and legal bases for your assertion that such secondary considerations (or objective indicia) apply; the nexus between any such identified secondary considerations and each asserted claim; identify by Bates number all documents relating to any purported secondary considerations (or objective indicia), including, but not limited to, those documents supporting or refuting your contention; and identify the individual(s) (at or employed by Plaintiff or under Plaintiff's control) most knowledgeable about each such consideration (or indicia).

RESPONSE TO INTERROGATORY NO. 3:

A response to this is premature. Among other things, related discovery is not complete. A more complete response to this shall be forthcoming in the Plaintiff's expert witness declaration and subsequent motion for summary judgment.

Plaintiff preliminarily asserts that the commercial success of the panoramic cameras made pursuant to licenses granted to Microsoft and Polycom by FullView show the commercial success of the inventions. Both companies touted the breakthrough nature of their devices in advancing the teleconferencing art. In fact, when the inventor visited the main office of Polycom in San Jose

and of its present parent, Plantronics, Inc. in Santa Cruz, in 2018–2019, to discuss a potential settlement of this action, an accused device, apparently the RealPresence Centro, was prominently showcased at each location, in an individual "conference room" adjacent to the lobby. That no one proposed or implemented the invention as described in claims 10-12 of the Patent-in-Suit prior to this patent despite active research in this field since at least 1960, and that Polycom's accused products are the only such products commercially offered, corroborate the non-obviousness of the invention. Whereas one motivation for the asserted claims was to reduce lens flare, the inventor subsequently realized, around 2005, that claim 10 offered an unexpected advantage: It increased the seamlessness of composite images geometrically too — in addition to photometrically — without requiring tighter manufacturing tolerances.

INTERROGATORY NO. 4:

For each asserted claim of the Patent-in-Suit, describe with full particularity the circumstances, including dates and individual(s) involved, in which the subject matter claimed was first made public, including the circumstances surrounding the first offer for sale of any claimed product, the first disclosure of the claimed subject matter to a noninventor (and identify such noninventor), the first description of the claimed subject matter in a printed publication anywhere in the world, and/or the first public use in the United States of the claimed subject matter; identify all facts and documents (by Bates number) that support or corroborate your response; and identify the individual(s) (at or employed by Plaintiff or under Plaintiff's control) most knowledgeable about each such act of making public, disclosure, or offer for sale.

RESPONSE TO INTERROGATORY NO. 4:

Before the filing of the patent application on August 28, 1998, the inventor and his employer at the time, Bell Laboratories, kept the invention in strict confidence. In or around May 2000, FullView sold to USC, through Panoram Technologies, FullView's first product, FC-1005, which used the patented invention. A photograph of this product from May 2000 (FULLVIEW002128) and related literature (FULLVIEW002044–2051) will be produced. FullView believes that this product still exists at USC (and Stanford and Princeton). This product

was demonstrated by USC in October of 2000 in a football game between USC and Cal. USC published papers (FULLVIEW002036–2043) on this, and promoted it (FULLVIEW002130), including through a video it produced using this product. There is no document describing the inventions that predates the patent application and these inventions were first implemented in the above-described product.

INTERROGATORY NO. 5:

Identify (by Bates number) any documents that the named inventor of the Patent-in-Suit, persons working under the named inventor's direction or control, and/or Plaintiff's considered in connection with the development of the alleged inventions described in the Patent-in-Suit, regardless of whether such documents were disclosed to the U.S. Patent and Trademark Office.

RESPONSE TO INTERROGATORY NO. 5:

In connection with the development of the inventions described in the asserted claims of the Patents-in-Suit, Dr. Nalwa does not recall considering any documents that were not disclosed to the patent office.

I declare under the laws of the State of California that the foregoing responses are true and correct to the best of my knowledge and belief, and that this declaration was executed in Saratoga, California, on September 22, 2021.

/s/ Vishvjit S. Nalwa

September 22, 2021 Vishvjit S. Nalwa

Dated: September 22, 2021

Respectfully submitted,

By: /s/ Bruce J. Wecker

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PROOF OF SERVICE

I, Season Shimizu, declare that I am over the age of eighteen (18) and not a party to the entitled action. I am an employee at the law firm of HAUSFELD LLP, and my office is located at 600 Montgomery Street, Suite 3200, San Francisco, California 94111.

On September 22, 2021, I served a true and correct copy the following:

PLAINTIFF FULLVIEW, INC.'S OBJECTIONS AND RESPONSES TO DEFENDANT POLYCOM, INC'S FIRST SET OF INTERROGATORIES

via electronic mail on the interested parties in this action addressed as follows:

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Attorneys for Defendant POLYCOM, INC.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on September 22, 2021 at San Francisco, CA.

/s/ Season Shimizu
Season Shimizu